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DUST-CLOUD EFFECTS ON AIRCRAFT ENGINES—EMERGING ISSUES AND NEW DAMAGE MECHANISMS (U)

A Case Study of a Mt. St. Helens Experience and its Implications for Nuclear-Weapon-Lofted Dust-Cloud Effects (U)

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The May 1980 eruptions of Mt. St. Helens produced high-altitude dust clouds that presented several difficulties to aircraft. Most consequences were fairly minor routing changes and flight delays, but some in-flight orifice clogging and abrasion damage was encountered. This report provides a short profile of the most severe incident: a Transamerica Hercules L-100 (C-130 equivalent) cargo aircraft lost two engines and suffered power losses in the two remaining ones after only a few minutes exposure to ashfall, well

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20. Abstract (Continued)

beneath the main cloud of the May 25 eruption and two hours after the eruption started. The damaged engines showed compressor section abrasion plus large amounts of melted dust coating the turbine section. Based on this experience, this report also raises concerns about aircraft vulnerability from dust clouds lofted by nuclear detonations. Finally, it is pointed out that a new damage mechanism may exist for turbine engines that is not covered by standard aircraft testing procedures. The possible and important radiation hazards to flight crews resulting from radioactive, late-time dust environments are not treated in this report. Only physical damage to aircraft engines is examined.

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PREFACE

The authors wish to thank Mr. H. Mitchell of IRT Corporation for raising this issue initially, as well as Dr. F. Gilmore (RDA) for his contributions to both Mr. Mitchell's work and to numerous aspects of this short research activity. We also gratefully acknowledge the contribution of two consultants, Dr. D. Oberste-Lehn (RDA) and Dr. G. Rawson (UC-San Diego), a geochemist. They worked on the Mt. St. Helens ash plume data acquisition and evaluation, and the C-130 aircraft engine data acquisition, and provided expertise in areas of soil composition, glassification processes and test plan formulation.

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I. INTRODUCTION

This report documents the results of a short investigation into the nature of late-time (i.e. fine-scale) dust effects on aircraft engines. More specifically, this research emphasizes the development of an initial understanding of the potential consequences of dust ingestion by air-breathing engines, as revealed by data collected from the Mt. St. Helens eruption of 18 May 1980. The principal focus was on understanding the nature of one particularly interesting incident--a C-130 aircraft that suffered severe engine damage following a few minutes exposure to the ashfall from a cloud produced by the eruption. The catalyst for this research was a previous set of observations documented in RDA-TR-120012-001 by H. Mitchell (IRT) and F. Gilmore (RDA). That study raised concerns about the late-time effects of nuclear-weapon-lofted dust clouds on aircraft engines. Accordingly, this work complements that original research. It is intended to provide a starting point for investigating the relationship between the phenomenon observed in this Mt. St. Helens incident and the possible effects of dust clouds from nuclear weapon detonations on the performance and endurance of aircraft with critical military roles. The endurance and airborne station-keeping capabilities of selected command-post, launch-control and communications aircraft has become the cornerstone of the strategic command and control systems to be employed in a nuclear war. If these capabilities were jeopardized by the widespread, late-time dust environments generated by the copious nuclear detonations expected in a nuclear war, the consequences could be catastrophic.

Based on the limited research reported herein, the following general observations can be made:

1. A detailed investigation of the C-130 encounter with the Mt. St. Helens dust plume showed that probable failure was initiated by compressor blade erosion and large amounts of melted dust coating the turbine section.

2. The dust environment was likely much denser in selected areas than anticipated in engine test specifications and was extremely inhomogeneous with a much different chemical composition and size-distribution.

3. New engines with higher turbine temperatures and cooled stator and rotor blades could be more susceptible to glassification problems.

4. The potential glassification problems to be faced by aircraft in nuclear-weapon-generated dust environments can only be classified by additional research--both in environment definition as well as through laboratory testing. It is recommended that such research receive high priority.

The basis for these observations is provided in subsequent sections of this report. Section II provides a detailed description of the Mt. St. Helens incident, with an assessment of the mechanism involved in engine damage. New damage mechanisms are described and the sensitivities of various engine types are discussed along with the chemical processes leading to the glassification of selected soil materials. Section III and associated appendixes present a brief, systematic development of the technical aspects of the nuclear-weapon-lofted dust environment and its potential for damaging air-breathing engines. Finally, Section IV presents a recommended experimental test plan for further clarifying these potential engine damage mechanisms in late-time dust environments.

II. AN AIRCRAFT ENCOUNTER WITH THE DUST PLUME FROM THE MT. ST. HELENS ERUPTION

An opportunity to investigate and document the damages to aircraft engines that ingested airborne volcanic particles was provided by the encounter of a C-130 aircraft with the eruption plume of Mt. St. Helens on 25 May 1980. Section II.1 provides an overview of this incident.

1. AIRCRAFT FLIGHT HISTORY

Transamerican Airlines (TA) Flight 222/146, an L-100 designated as aircraft 24ST, encountered a volcanic ash plume while en route from McChord AFB (Tacoma, Washington) to Travis AFB (near Oakland, California) on 25 May 1980. Miscellaneous documentation of this incident is included in Appendix A. The flight departed McChord at 3:37 a.m. (PDT) and was cleared to operate along a course [direct to Portland (PDX)] then southbound such that it would have passed about 15 nmi west of Mt. St. Helens in southwestern Washington. Flight conditions during the climb were in and out of stratified cloud layers (approximately at 7000 ft, 9500 ft and 12,700 ft). The flight was operated essentially during darkness, although it was beginning to become light.

About 12 min after takeoff (~3:49 a.m.) while climbing through 12,000 to 13,000 ft on a heading of 190°, the crew noticed a smell in the cockpit. Climb power and all engines were reported normal at that time. At about 13,500 ft between cloud layers, the captain reported seeing a "big cloud ahead of us and it goes way up." It looked grayish and more like a volcanic cloud than a typical weather cloud. At about 15,000 to 16,000 ft it began to get darker and the smell got stronger. At about 16,000 ft the captain notified Air Traffic Control (ATC) that he thought the unusual smell could be attributed to volcanic ash and that he was in IFR conditions. ATC provided

the aircraft with a right turn to a heading of 270°. The captain reported that they were still in the cloud (plume) and that it seemed to be as bad or worse than before.

Approximately 2 or 3 min thereafter, engine #4 made a backfire noise four or five times, and began to stall and surge. The cockpit was very dark, and explosions reflecting from the clouds lit it up very bright. All engine instruments were fluctuating. Engine operation became uncontrollable and engine #4 was shut down (feathered) at 3:53 a.m. Approximately 2 min later, engine #2 incurred the same type of failure and was shut down at 3:55 a.m. The captain decided to turn north and descend to McChord AFB. The aircraft became clear of the ash cloud shortly thereafter. Power on engines #1 and #3 was reduced, and several 260° turns were made to final approach. Aircraft 24ST arrived back at McChord at 4:14 a.m.

An ensuing inspection of the aircraft at McChord indicated that engines #4 and #2 had incurred compressor erosion and severe turbine damage also. All three forward windshields incurred severe abrasion and required replacement. Numerous components of the air conditioning system also required replacement. Additional remarks by the crew indicated that ash concentrations reduced visibility in the cockpit. The inside of the cowlings were covered with fine particles and dust, as was the inside of the cockpit. The tail pipes were blue and black, and the bottoms of the tail pipes had about a cupful of black shiny grains ranging in size from fine sand to small peas.

2. MT. ST. HELENS ERUPTION HISTORY

Mt. St. Helens is located east of and immediately adjacent to Jet 1 (14 nmi) between Seattle and Portland. The initial eruption on 25 May 1980 occurred between 1:20 a.m. and 1:52 a.m. (PDT), about two hours before 24ST left McChord AFB. Steam and ash emitted to 24,000 ft at the last reading taken. A subsequent major eruption occurred at approximately 3:00 a.m. A

weather bureau sequence report issued by Portland on May 25 at 3:03 a.m. indicated that radar was able to establish the presence of an ash cloud at 14,000 ft drifting northwest. It is unlikely that this report would have been available to the 24ST crew prior to their leaving McChord. Apparently this information was in the ATC System, but cautionary notems had not been issued. Radar was not used by 24ST on its departure from McChord; the reason given was that there were no indications of any meterological conditions that would have generated turbulence. The question arose later whether or not the radar could have been used to identify the ash clouds and thereby allow the pilot to avoid an ash encounter. Apparently, there is no definitive background on which to base such an assumption, and the radar reflectivity of volcanic ash as received by the airborne receiver is not known.

Subsequent to the 24ST encounter with the Mt. St. Helens plume, ATC issued a notem at approximately 4:30 a.m. closing a large area of northwest Oregon to aircraft operations from sea level to 40,000 ft. The area encompassed by this enclosure can be defined by a line running from Portland to Yakima, to Olympia, to Neah Bay, back to Portland.

3. AIRCRAFT-VOLCANIC PLUME ENCOUNTER

Insufficient and/or apparent discrepancies in the available data base do not permit a precise account of the relative positions of the ascending aircraft and the evolving volcanic plume. Depending on altitude, the erupted volcanic material was moving in a complex pattern due to variations in wind directions and velocities.

Airfall ash from the May 25 eruption was distributed over a 140° sector from the volcano, from azimuths 180° to 320° (Fig. 1). This wide distribution is a consequence of divergent wind directions with altitude above the volcano. The fast, higher level winds between altitudes of 5500 m and 15,000 m

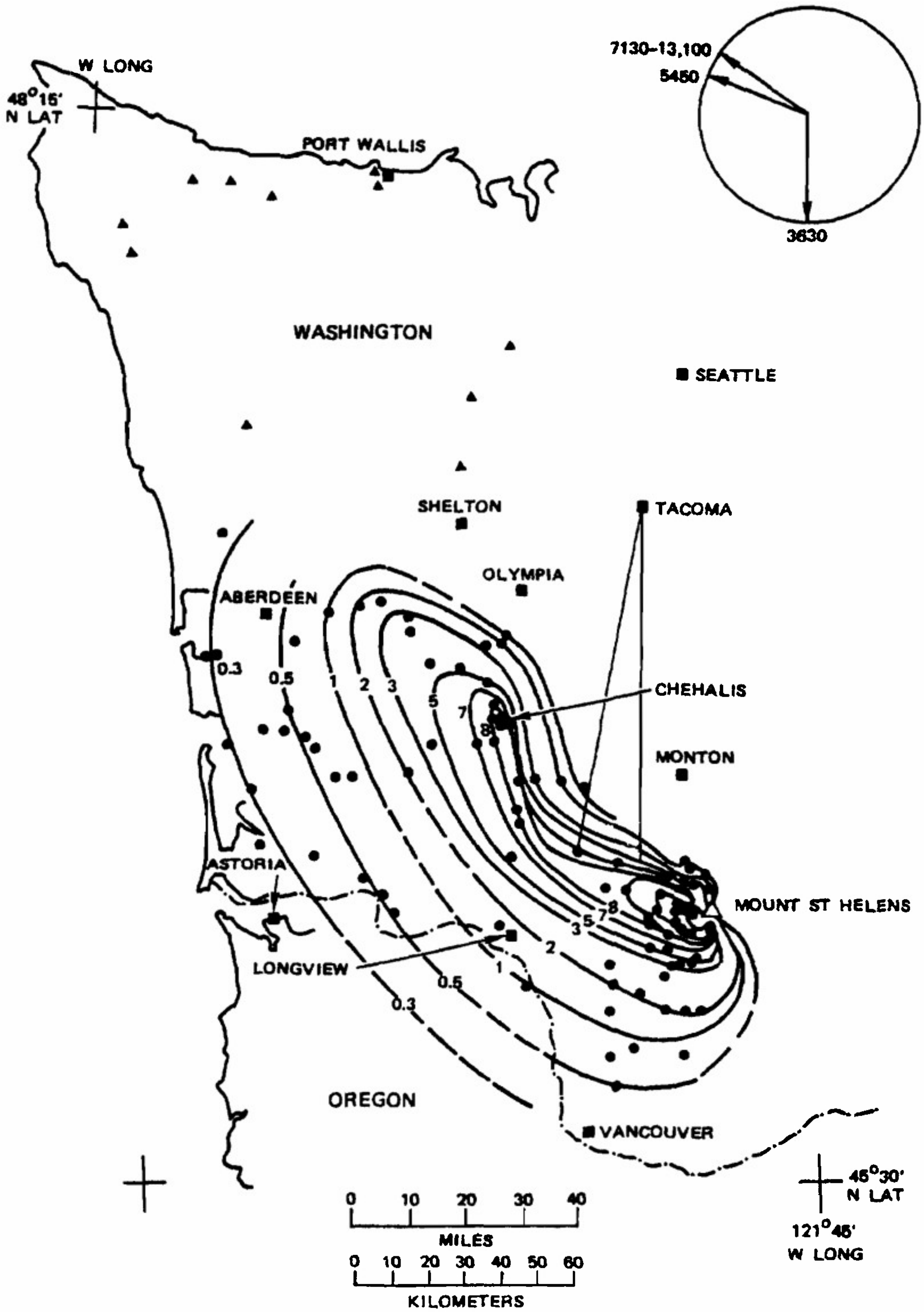

Figure 1. Volcanic plume from Mt. St. Helens.

(-18,000 ft and 50,000 ft) blew toward the northwest. The slower, lower level winds carried ash to the west, southwest, and south. (A secondary high in depositional thickness appears 70-80 km northwest of Mt. St. Helens.)

Several factors caused uncertainty in the flight path of the aircraft. Different sources quoted somewhat different values for the aircraft heading. The aircraft velocity was not known accurately, and the amount of drift was not known. Thus, the position of the aircraft was not well-established at the time of the encounter with the volcanic plume. Based on the available data, the aircraft appears to have encountered the plume on its northeast edge and not very far northwest from Mt. St. Helens, as shown on Figure 1. From the crew reports, the rapid failures of the two engines, and the fast changes in flight headings, the aircraft was not in the plume very long, probably around 8 min maximum. The condition of the remaining operating engines indicated that they would have failed also if the aircraft had remained within the volcanic plume a few minutes longer than it did.

4. AIRCRAFT ENGINE DAMAGE AND FAILURE

a. Engine damage evidence--The damaged engines, turbines, and compressors which were replaced have been discarded. Thus, the only evidence available are photographs of damage within some of the engines, a small section cut from one of the turbines, a small sample of volcanic ash removed from inside one of the engines (position not specified), and depositional material removed from around some of the thermocouples and from one of the vanes.

Engine #4, which was the first one to malfunction and be shut down, had to be replaced with a spare engine at McChord AFB. Figures 2 through 6 illustrate some of the damage to turbine engine #4. The first-stage vanes exhibit extensive

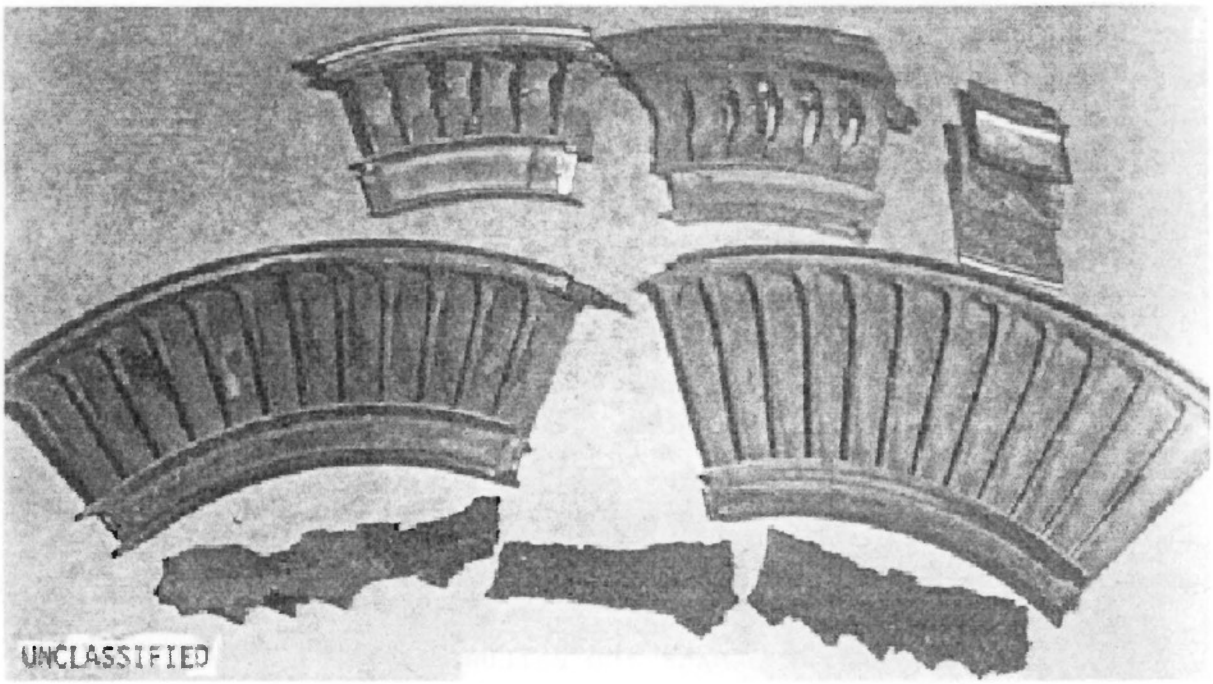

Figure 2. Portions of turbine stators, first through fourth stages.

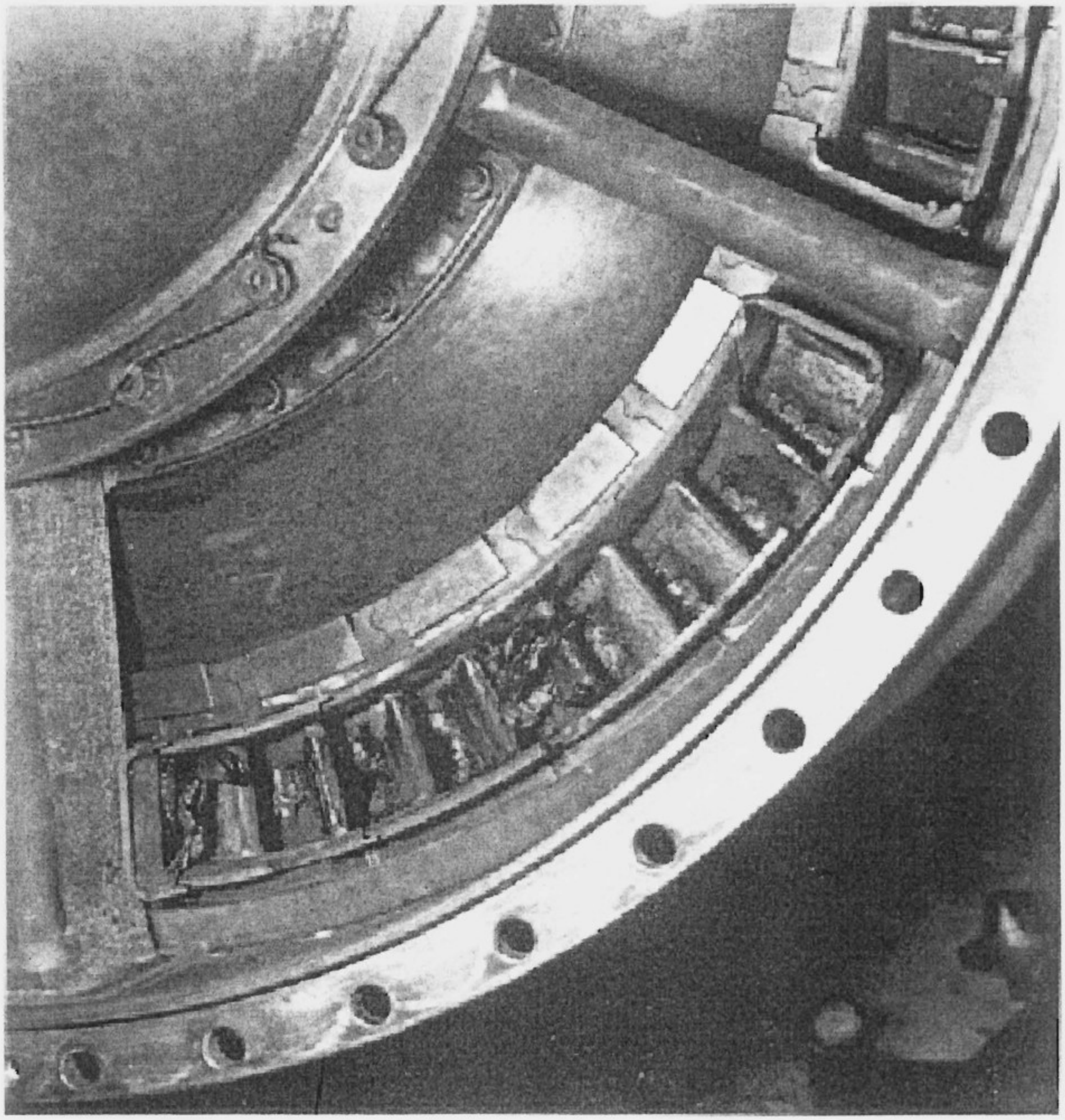

Figure 3. First-stage stators.

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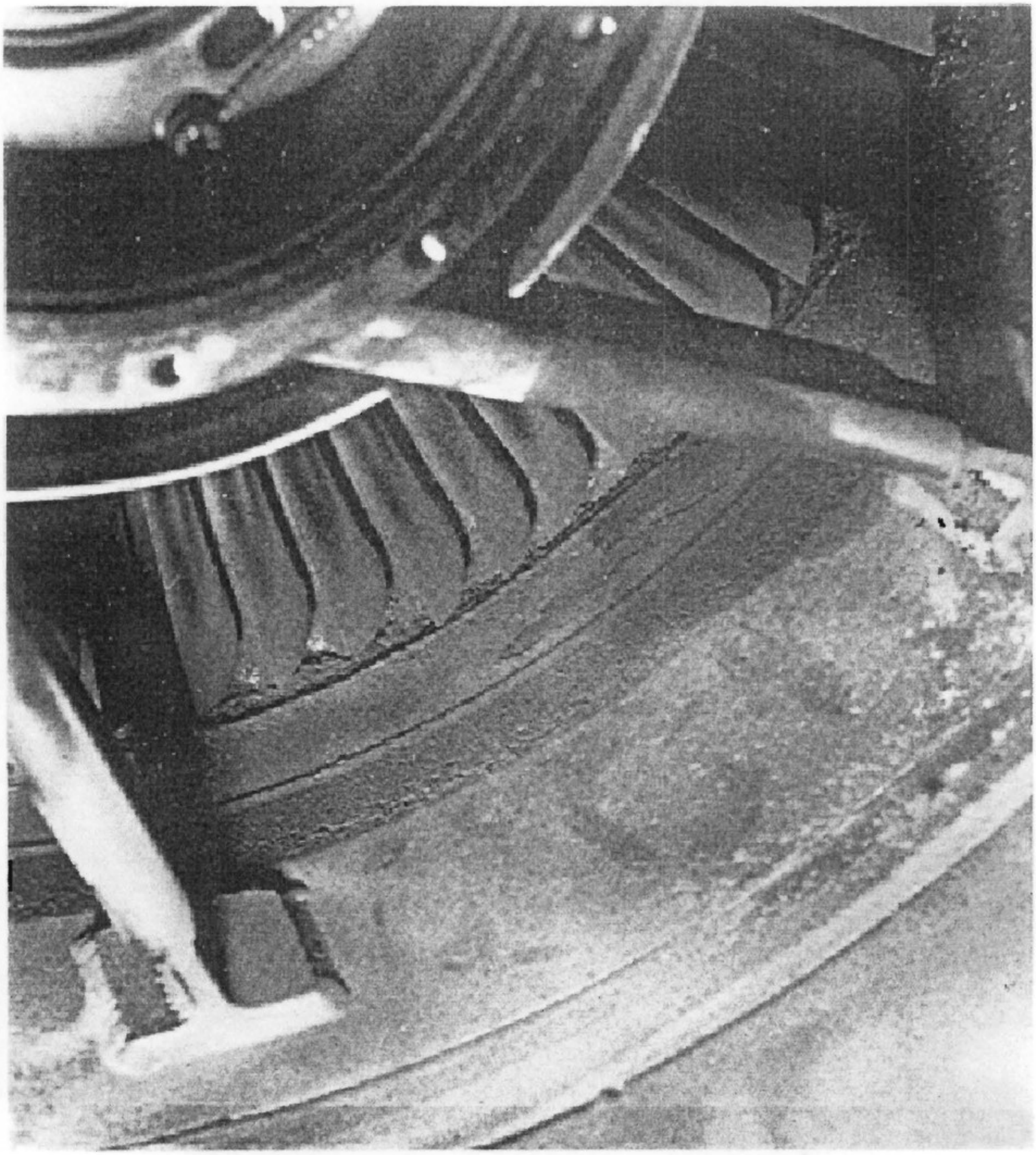

Figure 4. Turbine blades and housing.

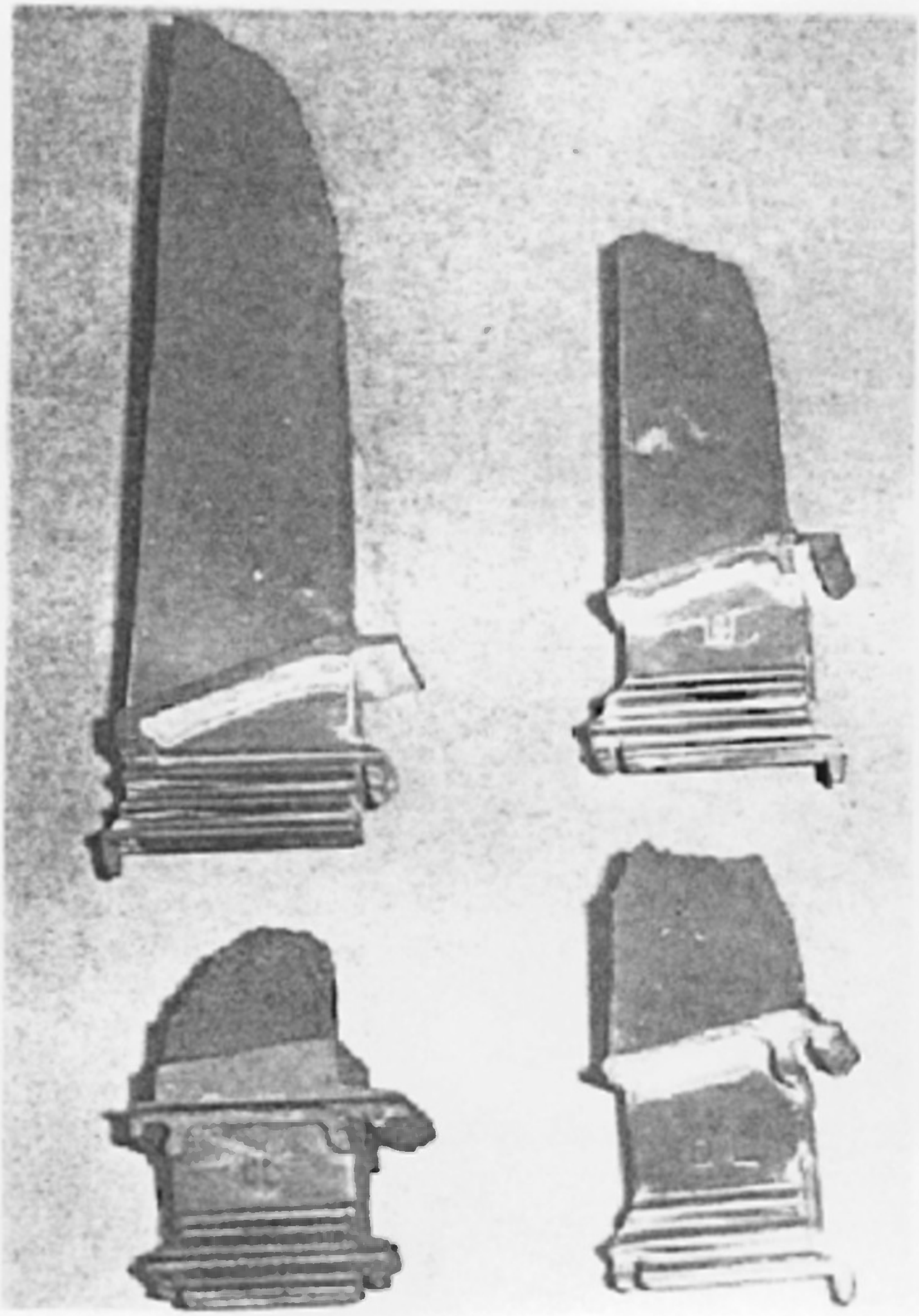

Figure 5. Turbine blades, first through fourth stages.

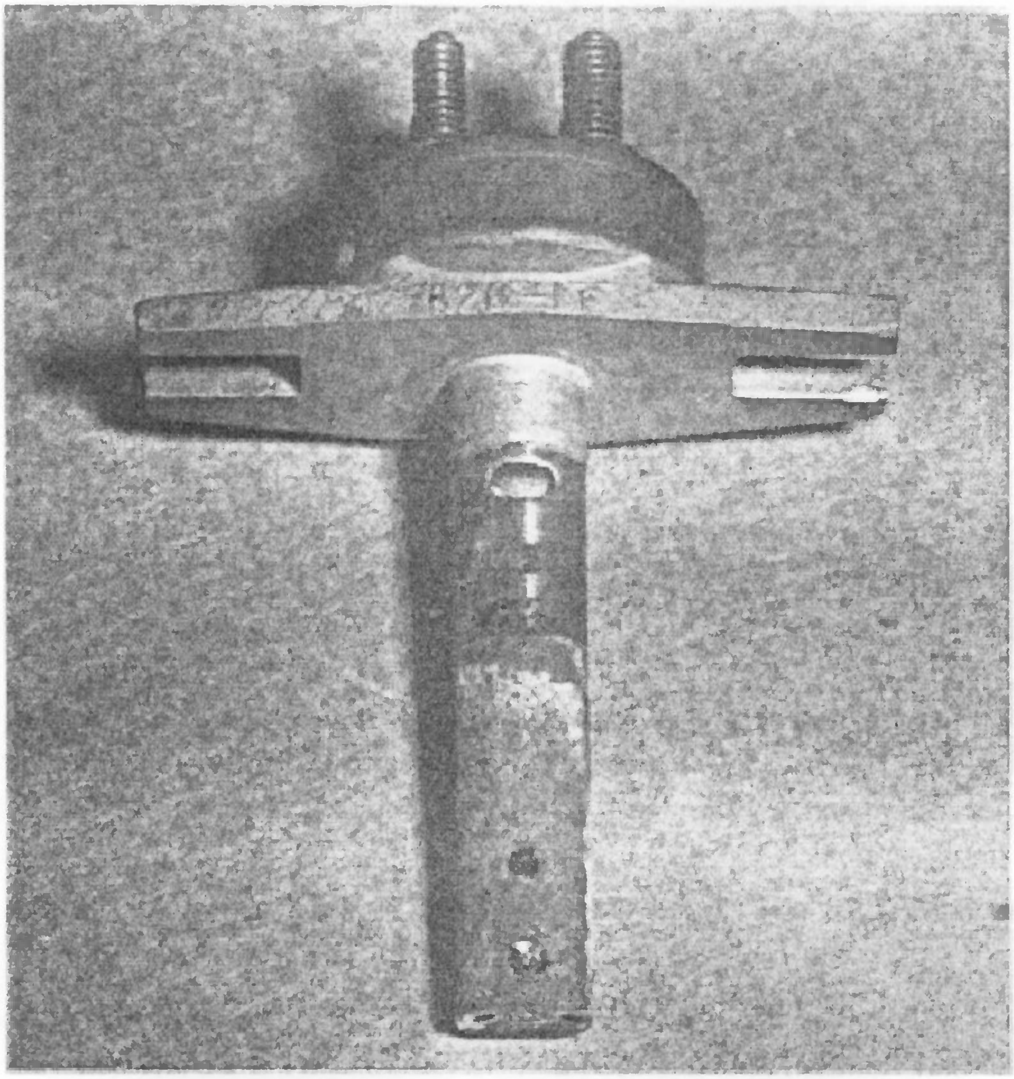

Figure 6. Turbine temperature probe.

deformation from deposition and erosion, and burned and cracked airfoils (Figs. 2 and 3). All second-, third- and fourth-stage vanes exhibit erosion (burn damage) to their airfoils (Figs. 2 and 4). All blade tips on all stages are eroded away (burned off) to varying degrees (Fig. 5). Thermocouple sampling orifices are plugged with deposited material (Fig. 6). This turbine reportedly had a heavy ingestion of volcanic ash.

Compressor #4 exhibited cracks in the air inlet housing at the 3 and 9 o'clock positions, eroded blade paths in the compressor case, erosion and slight foreign object damage (FOD) on all 14 of the vanes, erosion and slight FOD on trailing edges of all blades (stages 1 through 14), and grooves in the front compressor seal. This unit had heavy volcanic ash ingestion.

Engine #2, which was the second one to malfunction and be shut down in flight, had the same type of damage as engine #4. It was also replaced by a spare engine. The case lining on compressor #2 was eroded; it had light erosion of the vanes and blades and exhibited wear on two fuel-nozzle air shrouds. This unit had volcanic ash ingestion.

Engine #1 had overtemperature damage to the turbine, which was replaced. Turbine #1 exhibited excessive wear of five liner supports, five crossover ferrules, and three fuel-nozzle ferrules in the combustion liners. Moreover, it had twenty cracked and burned airfoils on the first-stage airfoil vanes and twelve on the second stage, and 102 burned and eroded leading edges of first-stage blades. This turbine reportedly also had heavy ingestion of volcanic ash. Compressor #1 could not be replaced, however, so the aircraft had to fly on three engines from McChord AFB to Oakland Airport.

Engine #3 also had overtemperature damage to the turbine, which was replaced. The compressor on engine #3 exhibited light

erosion, and was the only major component of the four engines that was used on the flight to Oakland after the plume encounter. A section of a second-stage vane, which had been cut out of one of the turbines before it was discarded, was extensively deformed, exhibiting a combination of erosion and deposition.

Depositional material wrapped around the thermocouples appeared to be single layers, some of which were about 5/32 in thick. Some depositional material lodged on one of the vanes had multiple layering, but was roughly wedge-shaped in thickness, the maximum thickness being greater than that around the thermocouples. Volcanic ash deposits were found inside the engines, a sample of which was analyzed for particle size and shape, mineralogic components, chemical elements, and melting points.

The sequence or rate of engine failure or damage is #4 (outboard right), #2 (inboard left), #1 (outboard left), and #3 (inboard right). The times in hours since overhaul of the turbines (T) and compressors (C) were: T4 - 543, C4 - 9835; T2 - 1910, C2 - 2910; T1 - 6906, C1 - 14,083; and T3 - 6147, C3 - 3647. There is no apparent relationship between engine failure and engine position or number of hours of flying time on the turbines and compressors.

b. An independent meteorological and chemical analysis of ingested ash--The bulk volume of material ejected during the 25 May 1980 eruption of Mt. St. Helens was 0.03 km^3, and the total mass was 0.42 x 10^{14} g (giving an uncompacted average bulk density of 1.03). The in situ rock volume prior to eruption would be between 0.016 and 0.022 km^3 (or about 0.08 that of the major May 18 eruption). The May 18 eruption produced a mass of 4.9 x 10^{14} g, and a minimum volume of 1.1 km^3 of the situ rock, assuming an average density of 2.0 to 2.6 gm/cm^3 for summit rocks and magma.

At Tampico, about 124 km northeast of Mt. St. Helens, a variety of particle sizes were measured from the May 25 eruption. The coarse fraction (>0.063 mm) peaked at about 0.12 mm; the fine fraction (0.002-0.0063 mm) peaked at about 0.004 mm; and the combined fraction (0.008-0.25 mm) peaked at about 0.01 mm. Most ash samples have bimodal size distributions with peaks at 0.002-0.008 mm and 0.008-0.125 mm. Size bimodality may reflect fine abrasion of the surfaces of large grains during eruption and transport.

Grain shape measurements (area/perimeter^2) interpreted as the degree of circularity indicate a statistically significant difference between the two measured size fractions. The fine-grained particles are distinctly more angular and/or elongate.

A sample of 24ST engine ingested volcanic ash from the May 25 eruption was analyzed at Stanford University for mineralogy, chemistry, particle size and shape, and melting temperatures. The report on these analyses is presented in Appendix B. Some results of the analyses can be summarized as follows:

- Particle size falls in the range of 0.50-0.05 mm.
- Most grains appear irregular in shape although they are roughly of equal dimensions.
- The sample is composed of several common silicate minerals plus some rock fragments and seems to be representative of typical volcanic ash material.
- The minerals present in the ash have values in the range of 5-6 on the Mohs hardness scale.
- The volume proportion of glassy material in the ash is estimated to be less than 5 percent.
- Grain appearance, a lack of visible evidence for partial melting, the determined melting temperature

range of 1200°C to 1400°C of the ash, and the nature of the constituent minerals indicates that this material had not been subjected to the temperature range of 1200°C to 1400°C of the ash; the nature of the constituent minerals indicates that this material had not been subjected to temperatures above 1000°C to 1100°C in the aircraft engine.

- Except for the anomalously high amounts of the metals discussed in Section II.4, the spectrographic evidence indicates a similarity in the major and trace elements between the ingested sample and other published data on ash from Mt. St. Helens.

5. SUMMARY

From the tangible evidence (photos and samples provided by G. Lewis of National Airmotive Corporation and R. Carruthers of TA) the perceivable damage to the turbines was a combination of deposition and erosion, and damage to the compressors was primarily erosional. Visual inspection of the depositional material and deformed turbine parts indicates that the ingested volcanic ash was softened and melted sufficiently to adhere to turbine parts and was mixed with engine material, which also was locally softened and melted. This depositional material has a metallic slag-like appearance and a physical configuration and structure characteristic of solidified molten metal and volcanic flow rock.

In the turbines the erosion and deposition processes appear to have involved several different mechanims, which complicate the deciphering of their relative impacts on engine damage and failure. Evidence of mechanical erosion was found in the analyses of the volcanic ash. This consisted of some very small elongated pieces of metal that were removed from the sample before the analyses, with the help of a 70 power microscope.

The chemical analyses showed abnormally high amounts of certain metals: cobalt, chromium, lead, copper, manganese, molybdenum, nickel, strontium and tin. Most of these metals can be traced to aircraft engine material.[*] The combustion liners are composed of AMS 5536: 47.5 percent Ni, 22 percent Cr, 18.5 percent Fe, 9.0 percent Mo, 1.5 percent Co, and 0.6 percent W. The turbine vanes are composed of AMS 5382 (Stellite 31): 54 percent Co, 25.5 percent Cr, 10.5 percent Ni, and 7.5 percent W. The rotating turbine blades (first and second stage) are composed of INCO 738, but we have data only on INCO 722 (which is similar): base of Ni, 15.5 percent Cr, 7 percent Fe, 2.5 percent Ti, and 0.7 percent Al. The compressor casing consists mostly of aluminum (about 90 percent), and perhaps some copper. Metals not accounted for readily are lead and tin, which occur in the solder that is not exposed to the air stream; copper, which may be from the compressor; and manganese, which may be from the thermocouples.

The most impressive visual evidence of erosion in the turbine was due to abnormally high temperatures that softened and partially melted turbine parts, which either were deformed or were expelled from the rear of the engine. The proportional amounts of engine material eroded mechanically or by melting is not known. The short time that the aircraft was flying inside the volcanic plume, and the small size of the ash and metal particles observed afterward, however, suggests that mechanical erosion was unlikely to be rapid. Incidents of other aircraft flying through sand storms without having to abort also suggest that mechanical abrasion probably was not the critical factor in precipitating engine failures. On the other hand, once the temperature in the turbine region is raised sufficiently to cause damage--cracking, softening,

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[*]G. Lewis, personal communication, May 1981.

melting--it seems possible that turbine destruction could escalate rapidly, as dislodged pieces or molten metal flew through the turbine and damaged portions downstream.

The turbine operates at temperatures much higher than the compressor (Fig. 7). Several phenomena can adversely affect the turbine function. For example, combustion instability could cause "torching" of the turbine components. Deposition on the turbine parts could also throttle the airflow and force the engine into surge. Deposition of material on the thermocouples causes their malfunction, which can negate the over-temperature safety control mechanism. If the temperature at the engine surfaces rises too high, the metal can melt and deposit downstream, causing additional problems.

Carruthers, who determines the causes and extent of aircraft engine damage and assesses repair capability and costs for TA, believes that deposition resulting in excessively high temperatures ultimately led to the engine failures on the May 25 flight. If there had not been such a high temperature buildup, there would have been a power drop in the engines, but not the critical surge that necessitated engine shutdown. Deposition on the leading edges was deemed a major contributing factor to the surge.

The compressor is made of corrosion-resistant steel which has a series of aluminum strips in the case lining. This aluminum veneer, about 0.004 in thick, is designed to be soft. The steel blades and casing are finely milled to a narrow separation which is closed due to heat (metal expansion) and centrifugal force when the engine is operating. The blade ends have a 90 degree cut with sharp edges.

Normal long-term erosion tends to be evenly distributed on the parts (Carruthers). The very short-duration and intensive erosion caused by the ingested volcanic ash, however, preferentially eroded the soft aluminum case lining.

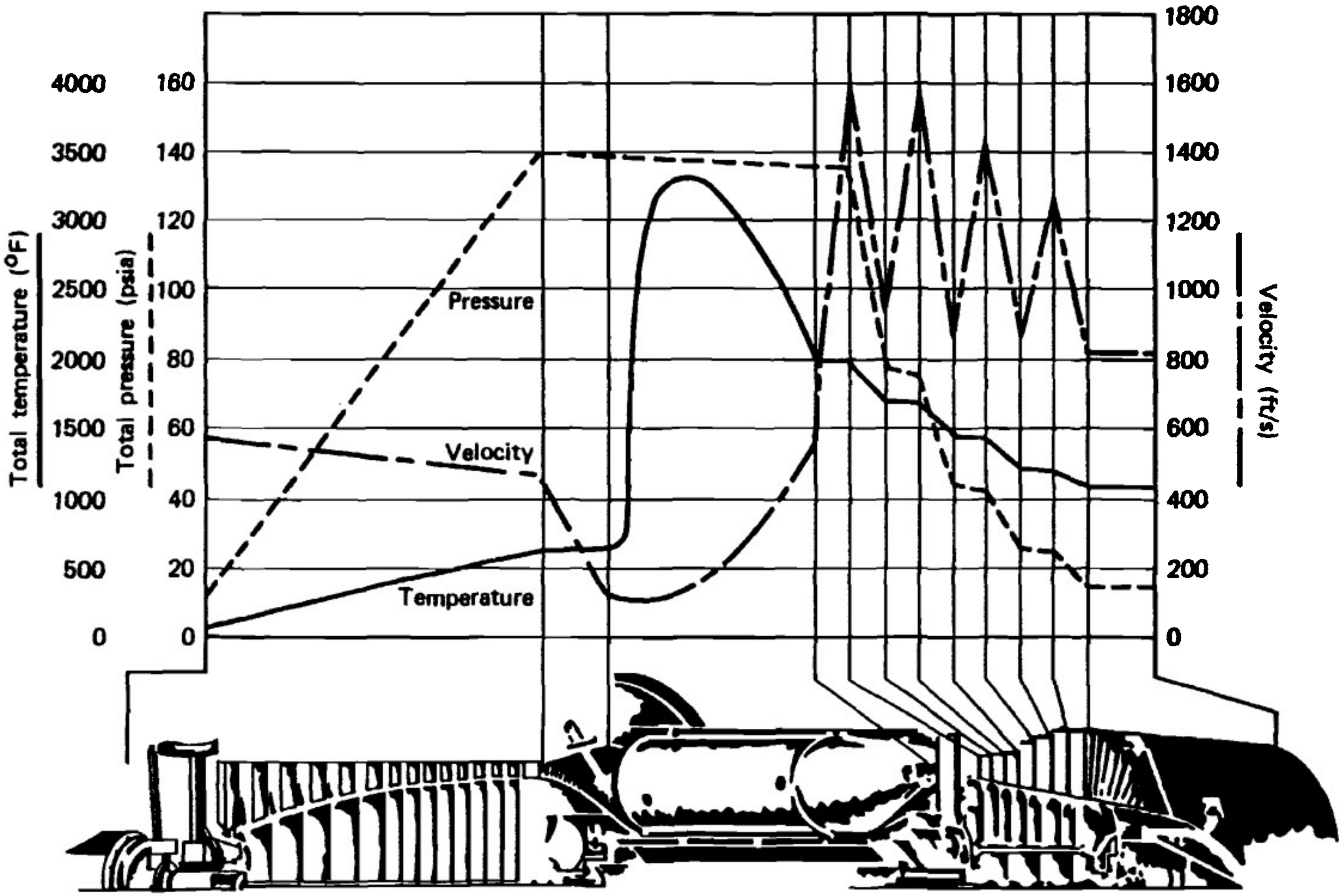

Figure 7. Temperatures, pressures and velocities in a 501-K13 or K-15 engine (equivalent to a C-130 engine).

The volcanic ash analyzed had very abrasive characteristics. Most of the particles were irregularly shaped, although roughly equidimensional, and had an angular or subangular outer surface. About 10 to 20 percent of the sample consisted of fragments or entire single crystals which had flat surfaces. These crystals commonly were elongate in one direction. The major minerals comprising the sample have a hardness around 6 on the Mohs scale. Particle size ranged from about 0.05 to 0.50 mm. The ingested volcanic ash gouged out the relatively soft aluminum, which opened the seal between the rotating blades and casing, thus impairing compressor efficiency.

Compressor temperatures during normal engine operation do not rise high enough to soften or melt volcanic ash. From the ash sample analyzed, the melting temperature was determined to be in the range of $1200^{\circ}C$ to $1400^{\circ}C$ in the aircraft engine. Although the location from which the ash sample was taken is not known, the analysis indicated that the ingested volcanic ash became lodged within the compressor or some other part of the engine having a temperature $>1100^{\circ}C$ and not downstream from any portion of the engine having temperatures $>1100^{\circ}C$.

Extrapolating the consequences of the above effect (and its underlying phenomena to aircraft operations in a nuclear environment is not trivial. Considerable uncertainties exist in every step of the extrapolation procedure. In Section III a brief introduction to the phenomena that must be understood in making this extrapolation is provided. Appendix C also summarizes the material previously discussed within the context of the potential problems that could occur during operations in a nuclear environment.

III. TECHNICAL IMPLICATIONS FOR NUCLEAR-WEAPON-LOFTED, LATE-TIME DUST CLOUD EFFECTS

An annotated briefing entitled "Aircraft Engine Nuclear Dust Ingestion," (Appendix C) provides a systematic presentation of the extrapolation of the Mt. St. Helens example into the nuclear-weapon-induced dust cloud environment. The underlying technical aspects of this extrapolation are briefly treated below.

1. ENVIRONMENT DESCRIPTION

We imagine that a mass M of dust has been lifted to stabilization altitude by one or more surface nuclear bursts. We are interested in the "fallout" region as distinguished from the stem or pedestal region, and will eventually inquire as to the rate of ingestion of dust by a low-flying aircraft cruising under the cloud proper. Figure 8 depicts the geometry.

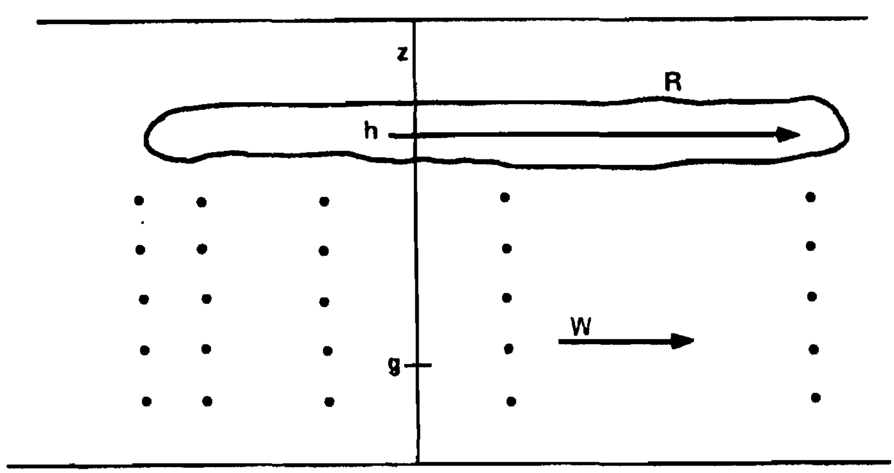

Figure 8. Dust cloud geometry.

Let $f(\mu)d\mu$ be the fraction of particles of diameter μ within $d\mu$ in the cloud after stabilization. By definition,

$$\int_{\mu_0}^{\mu_1} f(\mu)d\mu = 1, \tag{1}$$

where μ_0 is the smallest particle (μ_0 ~ 10-50 u) and μ_1 the largest (μ_1 ~ 1000 μ). If ρ is the dust particle density ($\rho \approx$ 2.5 gm/cm^3), then the mass M of the initial stabilized cloud is

$$M = \frac{\pi}{6}\rho N \int_{\mu}^{\mu_1} f(\mu)\mu^3 d\mu \quad , \tag{2}$$

where N is the total number of dust particles in the cloud. For simplicity we assume

$$f(\mu) = k\mu^{-4} \tag{3}$$

where k is a constant. This constant is determined by Eq. (1) to give the relationship,

$$\left. 1 = k \, \frac{\mu_0^{-3} - \mu_1^{-3}}{3} \right\} \quad . \tag{4}$$

For $\mu_1 >> \mu_0$,

$$k = 3\mu_0^3 \quad . \tag{5}$$

From Eq. (2) the mass M in the cloud is

$$M = \frac{\pi}{2}\rho N\mu_0^{\ 3}\ \ln\left(\frac{\mu_1}{\mu_0}\right) \quad . \tag{6}$$

2. DUST DENSITY

The arrival time of a dust particle originating at altitude h and passing through z as shown is

$$t_a(\mu,h,z) = \int_z^h \frac{dz}{v(z,\mu)} \quad , \tag{7}$$

where $v(z,\mu)$ is the fall rate of a particle of diameter μ at altitude Z. Figure 9 shows arrival time to the ground for the indicated starting altitudes as a function of particle diameter. We can roughly fit this curve with a power law,

$$t(\mu) = t_r\left(\frac{\mu}{\mu_r}\right)^{-3/2} \quad , \tag{8}$$

where μ_r is some reference particle diameter.

Now, the dust concentration $n(z,t)$ is

$$n = \frac{Nf(\mu)d\mu}{\pi R^2 dz} = \frac{Nf(\mu)}{\pi R^2 v}\frac{d\mu}{dt} \quad . \tag{9}$$

Thus,

$$n = \frac{3N\mu_0^{\ 3}}{\pi R^2 v}\ \frac{1}{T_r\frac{3}{2}}\ \frac{\mu^{5/2-4}}{\mu_r^{\ 3/2}} \tag{10}$$

$$n = \frac{2N\mu_0^{\ 3}}{\pi R^2 v T_r}\ \frac{\mu^{-3/2}}{\mu_r^{\ 3/2}} \quad . \tag{11}$$

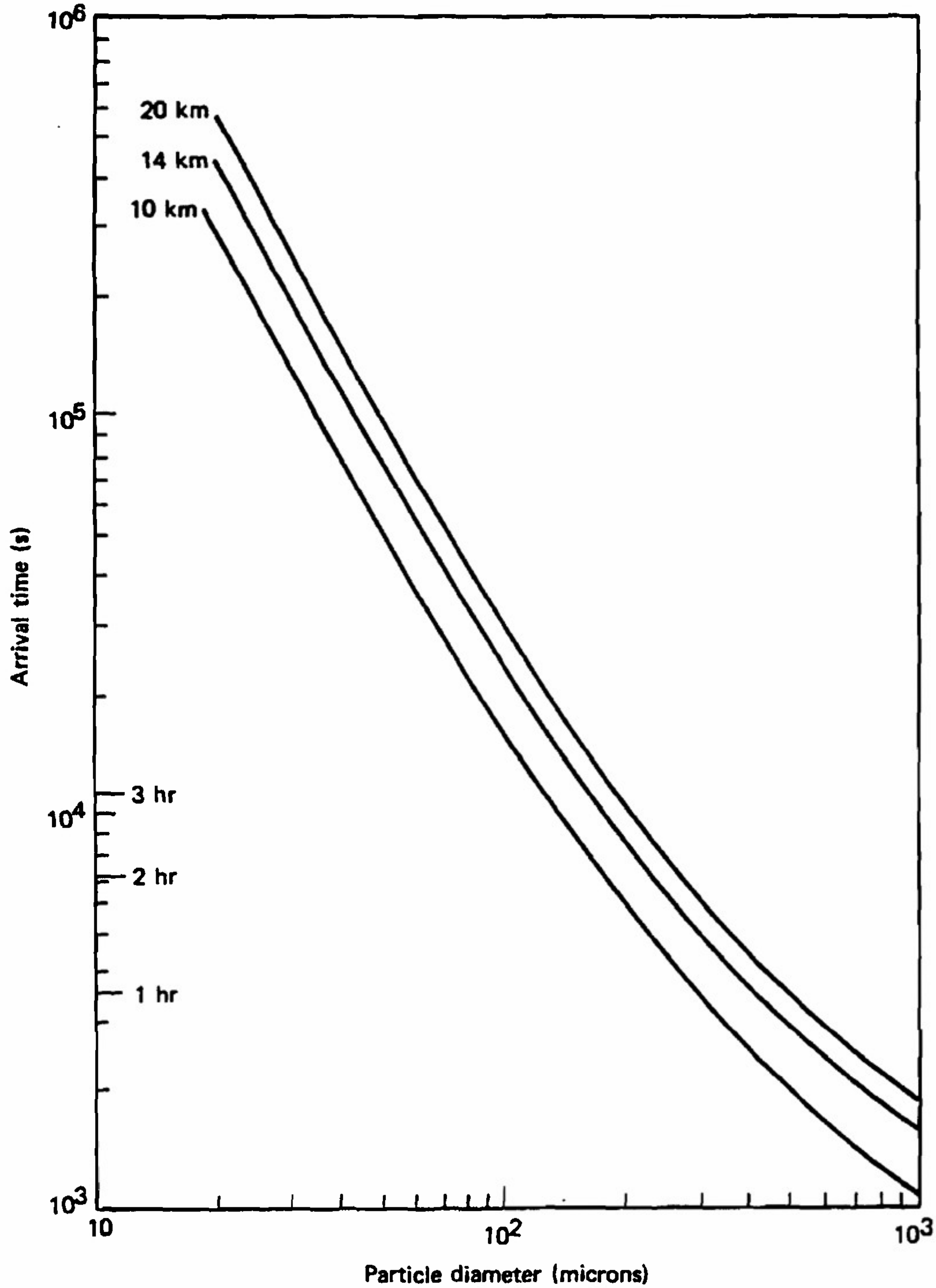

Figure 9. Arrival time as a function of dust particle size from the indicated altitudes.

Substituting for N from Eq. (6) yields:

$$n = \frac{2}{\pi R^2 v T_r} \, \frac{\mu^{-3/2}}{\mu_r^{3/2}} \, \frac{2M}{\pi \rho \ln \frac{\mu_1}{\mu_0}}$$

$$n = \frac{4 \, M \, \mu^{-3/2}}{\pi^2 R^2 v T_r \rho \ln \frac{\mu_1}{\mu_0} \mu_r^{3/2}} \; . \tag{12}$$

3. DUST INGESTION AND GLASS BUILDUP

Let n be the fraction of particles of diameter μ that sticks to the aft turbine blades and let ℓ be the thickness of the glass layer. Then,

$$A_1 \dot{\ell} = W A_0 n \eta \frac{\pi}{6} \mu^3 \tag{13}$$

where A is the blade area; A_0 is the turbine intake area; W is the aircraft speed; and η is the particle sticking probability. Noting that

$$\frac{d\ell}{dt} = \frac{d\ell}{d\mu} \frac{d\mu}{dt} \; ,$$

and substituting for the number density n from Eq. (12),

$$\frac{d\ell}{d\mu} = \frac{M}{\pi R^2} \, \frac{A_0}{A_1} \, \frac{W}{v_r} \, \frac{1}{\rho} \, \frac{\mu^{-(1+c)} \mu_r^{\,c}}{\ln\left(\frac{\mu_1}{\mu_0}\right)} \, \eta \; , \tag{14}$$

where we fit the fall speed to the particle size by

$$v = v_r \left(\frac{\mu}{\mu_r}\right)^c \; . \tag{15}$$

If we imagine that an aircraft ingests particles of size μ_α to μ_β , corresponding to spending a time under the dust cloud of $t_\alpha < t < t_\beta$, we have

$$\ell = \frac{M}{\pi R^2} \frac{A_0}{A_1} \frac{W}{v_r} \frac{1}{\rho} \frac{1}{\ln\left(\frac{\mu_1}{\mu_0}\right)} \frac{1}{c} \left\{ \left(\frac{\mu_r}{\mu_\alpha}\right)^c - \left(\frac{\mu_r}{\mu_\beta}\right)^c \right\} \eta \quad . \qquad (16)$$

4. NUMERICAL EXAMPLES

As a numerical example let us take a 1-MT burst, assuming a dust cloud of loading 1/3 MT/MT. Table 1 shows the cloud parameters at the indicated times. Also shown is the size of the particle and the fall rate at sea level (z = 0). The cloud area (πR^2) is denoted by A_c.

From Eq. (12) with $\mu_r = 100\ \mu$ and $T_r = 1.5 \times 10^4$ s, we evaluate the number density n and the dust loading ρ_0, expressed in milligrams per cubic foot. The results are shown in Table 2.

a. <u>Glassification</u>--As an example, let us consider an aircraft in the dust cloud at a time 1.67 hr to 4 hr after cloud stabilization. In Eq. (16) this corresponds to $\mu_\alpha = 100\ \mu$ and $\mu_\beta = 200\ \mu$. Take $A_0/A_1 = 10$, W = 150 m/s, c = 1 and $\mu_r = 200\ \mu$. Then,

$$\ell = 0.22\, \bar{\eta}\, (\text{cm}) ,$$

where $\bar{\eta}$ is the average sticking probability expressed in percent. Thus, if 1 to 10 percent of the particles condense on the cooler aft blades of a turbine engine, one can expect a buildup of a few millimeters to a few centimeters on the blades.

TABLE 1. CLOUD PARAMETERS

t (h)	t (s)	A_c (nmi^2)	A_c (cm^2)	μ (microns)	v (cm/s)
¼	9×10^2	3×10^2	1×10^{13}	600	500
1	3.6×10^3	1.2×10^3	4×10^{13}	200	150
3	1.1×10^4	3.6×10^3	1.2×10^{14}	100	56
10	3.6×10^4	1.2×10^4	4×10^{14}	40	15
24	8.6×10^4	2.9×10^4	9.7×10^{14}	30	6

TABLE 2. DUST LOADING AS A FUNCTION OF TIME

t (s)	n (cm^{-3})	ρ_D (mg/ft^3)
9×10^2	3.10^{-5}	2.4×10^{-1}
3.6×10^3	1.3×10^{-4}	3.9×10^{-2}
1.08×10^4	3.3×10^{-4}	1.2×10^{-2}
3.6×10^4	1.5×10^{-3}	3.5×10^{-3}
8.6×10^4	2.3×10^{-3}	2.3×10^{-3}

b. Thermal diffusion--The classic solution for the temperature rise of a spherical particle immersed in a heat bath of temperature T_0 is

$$T(r,t) = T_0 + \frac{2T_0 a}{\pi r} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} e^{-\frac{n^2\pi^2 kt}{a^2}} \sin\left(\frac{n\pi r}{a}\right) ; \tag{17}$$

here k is the diffusivity defined by

$$k = \frac{K}{\rho C_p} , \tag{18}$$

where K is the thermal conductivity and C_p the specific heat. As an example, with the following values

$$K = 10^{-3} \frac{\text{cal}}{\text{cm.s.}^0\text{K}} ,$$

$$C_p = 0.2 \frac{\text{cal}}{\text{gm}^0\text{K}} ,$$

$$k = 2\text{x}10^{-3} \text{ cm}^2/\text{s} ,$$

the fundamental time scale is

$$\tau_1 = \frac{a^2}{\pi^2 k} = 3\text{x}10^{-4} \text{ s} \tag{19}$$

for a particle of 25-μ radius. Since the residence time of a particle passing through a turbine engine is measured in milliseconds, it is evident from Eq. (19) that there is ample time for softening if not for fully melting.

The temperature from Eq. (17) is plotted on Figure 10 in dimensionless units. The dimensionless temperature $T(x,\tau)$ is

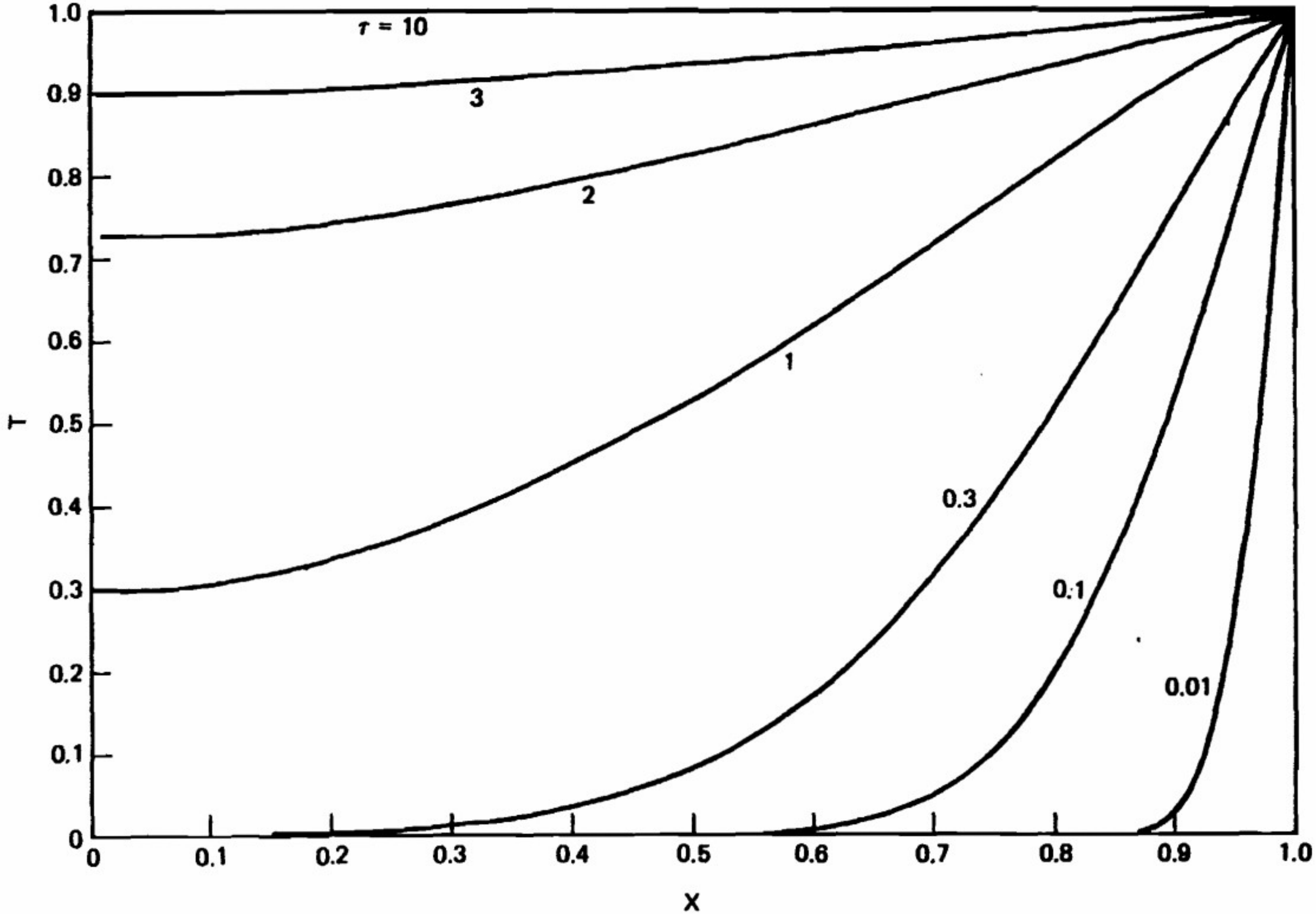

Figure 10. Temperature as a function of radius for the indicated times (dimensionless units).

[redacted]

[redacted]

$$T(x,\tau) = \frac{T(r,t)}{T_0} \tag{20}$$

where

$$x = \frac{r}{a}$$

$$\tau = \frac{t}{\tau_1} \quad . \tag{21}$$

5. DISCUSSION

The evidence indicates that the L-100 aircraft engines sustained severe damage resulting in mission abort after a very short exposure to the volcanic eruption material. Assessment of the damaged engines indicated that excessively high temperatures were primarily responsible for the series of events that lead to engine failure, and that the high temperatures resulted from several phenomena traced to ingested material which caused malfunction of thermocouples (deposition) and changes in airflow characteristics (deposition, erosion, air/fuel/particle ratios). The elements of a program designed to evaluate the potential of aircraft engine damage in a postnuclear ground dust environment is described in Section IV.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

The new damage mechanisms that were observed are described below:

- The melting of particles within a jet engine and their subsequent deposition on turbine blades and stator blades and turbine temperature/pressure sensors is a new damage mechanism. It was first seen in this incident and is due to the differing points of some volcanic components relative to the sand (quartzite) used in engine qualification tests.*
- Chemical/mineralogical analyses of material from damaged turbines showed it similar to common surface soils throughout the United States.
- There is presently no test criteria for damage due to the dust melting/cratering mechanism or events triggered by it.
- Engine design technology trends may make future engines more sensitive to these new damage mechanisms.

These are some concerns for aircraft operation in a post-attack nuclear environment:

- Surface and near-surface nuclear weapon detonations can loft large amounts of dust to high altitudes (40,000- to 60,000-ft altitude or more for a megaton-yield device).

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*Abrasion from sand has long been recognized as a damage mechanism and engine specifications were created during the Vietnam War in response to helicopter engine losses to protect against normally encountered ingestion levels.

- Known strategic target regions (i.e., missile fields) may have many tens to hundreds of nuclear weapons targeted against them. Aircraft in the vicinity of these areas may face severe dust cloud environments created by large numbers of spatially localized nuclear detonations.

- In a nuclear postattack period very large areas not near regions of intense attack exist where accumulated dust levels and persistent ingestion may threaten aircraft.

2. RECOMMENDED THEORETICAL RESEARCH

The following areas are suggested for further research into late-time environments.

- Predictions of the late-time nuclear-weapon-generated dust environment must be improved. Single-burst calculations that emphasize the period from several minutes to several hours or more after the detonation must be improved. Emphasis on fine-scale particulates and soil composition for various regions of the United States (and other countries, e.g., Europe and the Soviet Union) should be increased. Techniques for bounding cloud composition and densities parametric in meterological conditions must be developed and uncertainty estimates made.

- Based on the above, multiburst calculations of various wartime scenarios should be made (and non-scenario-dependent uncertainties estimated) so that a U.S.-wide portrait can be made of the potential evolution (after many hours) of late-time dust environments in which strategic aircraft may be forced to operate.

Based on the above there is a need to develop mitigation techniques so we can have a clearer understanding of the mechanisms and engine sensitivities to be derived from the experimental program described in Section IV.3. New designs, diffraction techniques or operational avoidance procedures (using onboard sensors to help in avoiding the dust regions) must be developed and field tested.

3. RECOMMENDED INITIAL (SMALL-SCALE) EXPERIMENTAL RESEARCH

The previous sections concluded that glass deposition in the turbine section of aircraft engines subject to certain types of dust environments could pose an unusually severe hazard. Furthermore, this could be particularly serious for certain military aircraft that must fly through the late-time fallout from perhaps a few-thousand-megaton attack on the land-based ICBM force. The exact mechanism and specification of this hazard is not fully understood, and both theoretical and test programs are required to illuminate our understanding of the problem.

The recommended program focuses mainly on the glass deposition effect, but the associated abrasion problems are also of concern. Abrasion effects have been well recorded and tested and an engine specification developed (MIL-E-5007D). However, a determination should be made of the relevance of these specifications to nuclear clouds, which could contain glass particles with abrasive properties possibly differing from those of the quartz sand defined for the engine acceptance specification (see Appendix D for further details).

a. <u>A possible test rig</u>--An integral part of the suggested program is a rig test to demonstrate and quantify the glassification process. In order to design a suitable test rig and formulate a test plan, a visit was made to Solar (a Division of International Harvester, San Diego), which was known to

have carried out hot abrasion tests on turbine engine components. It was found that Solar indeed had much of the auxiliary hardware, such as hot air and fuel supplies, dust injection equipment, and instrumentation that would be required for such a rig.

A proposed rig is shown in Figure 11. This sketch was drawn up after discussions with J. Shekleton, who is in charge of combustion engineering at Solar. The rig consists of a 12-ft-long tubular section which receives preheated air into a 6-in-diameter section, the latter ending in a combustor burning natural gas. The combustor discharges hot gas (turbine inlet temperature equivalent) through a water-cooled nozzle to impinge on the test sample at a velocity of about 500 ft/s. Dust particles are injected into the air stream by a dust gun which has been developed by Solar for hot erosion tests. The proposed test sample is a length of 1/4-in tubing of high-temperature metal (e.g., inconel) which can be cooled by a shop air supply as shown. The discharge air is finally collected into an exhaust silencer. Full instrumentation is supplied to determine temperatures, pressures and velocities as appropriate. Although primarily intended as a glass deposition test rig, comparative erosion tests could also be carried out if required by using the rig in a cold air configuration.

b. Rig test examples--The following test program is recommended for a first cut investigation.

(1) Run 1--Tests should be run on ground glass particles. This will give a pegpoint using a well-known and controllable substance. The size distribution and concentrations used should be based on a best estimate of the distribution of the late-time fallout from a massive attack on the ICBM sites. The burner temperatures should be typical of

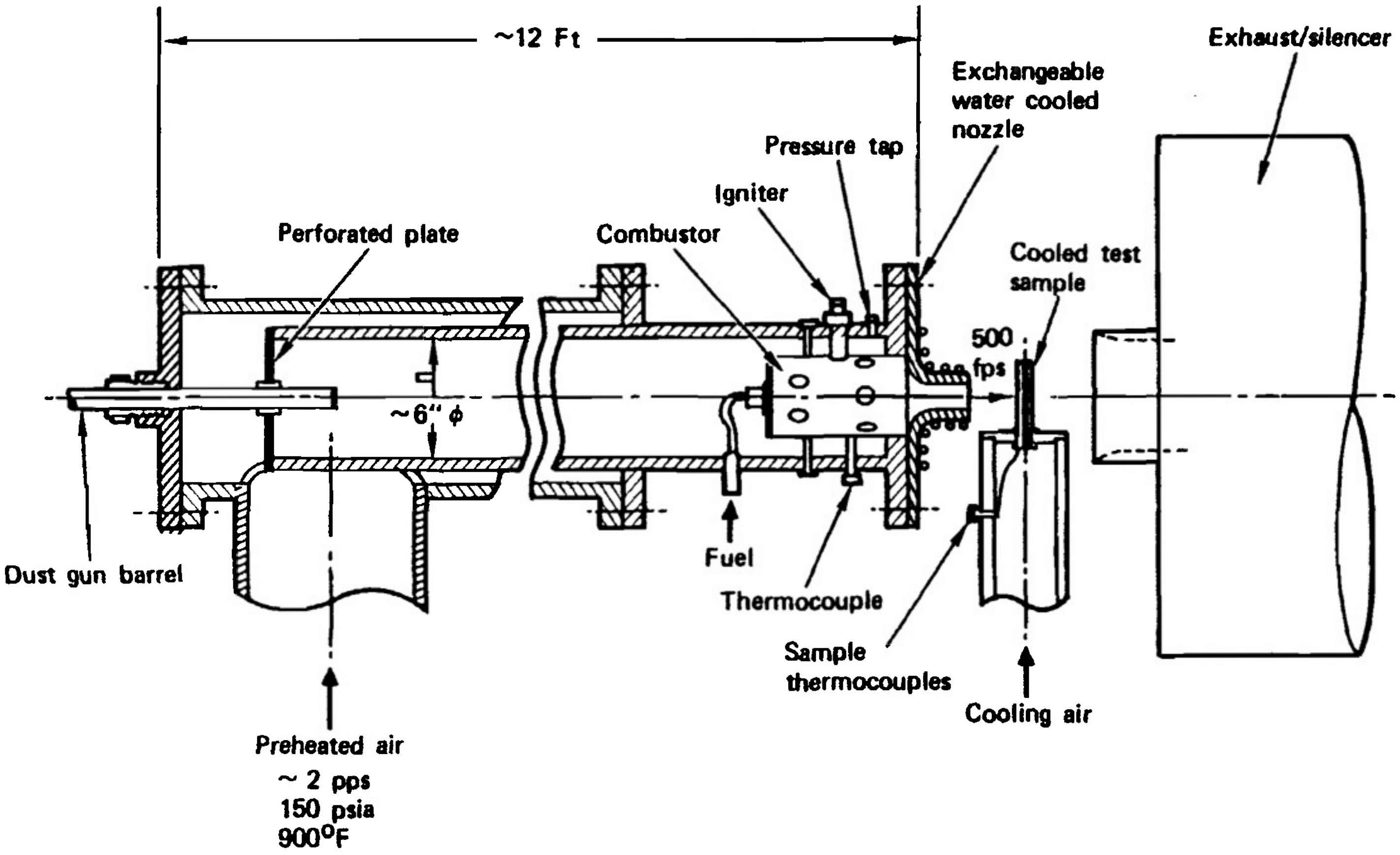

Figure 11. Schematic - glassification combustion testing.

current and projected turbine inlet temperatures and the test sample should be typical of cooled blade temperatures. As shown in the test criteria below, it is suggested that three burner temperatures and three sample temperatures with three dust concentrations be used as a baseline test guide to determine conditions under which glassification can occur. However, it may be necessary to revise these bounds as the tests proceed.

This first is a "go no go" test. It is expected that glassification will occur; but if it should not, the project should be carefully reexamined to determine further procedures or to recommend discontinuation.

(2) Run 2--A series of tests should be run on Mt. St. Helens dust and on likely dust compositions and distributions from ICBM attack scenarios. The matrix shown in Table 3 suggests the test parameters to be run.

TABLE 3. SUGGESTED PARAMETERS FOR DUST GLASSIFICATION TESTS

Test number	Dust character			Burner exit temp (°F)	Sample temp (°F)
	Dust	Dist.	Conc.		
I. 1.	Ground glass	E	E_1	2000 2250 2500	1000, 1300, 1500
2.		E	1/4 E_1	X	X
3.		E	4 E_1	X	X
II. 1.	Mt. St. Helens	H_1	H_2	A	A
			H_3		
2.	MX sites	X_1	X_2		
			X_3	A	A
3.	MM sites	M_1	M_2		
			M_3		

The "pegpoint" tests (I) are fairly easily defined. The best estimates of likely nuclear cloud distributions and concentrations are represented by E and E_1, respectively. It is proposed that runs be made at 1/4 and 4 times the expected concentrations, the latter run at burner and sample temperatures selected from the first test run as indicated. The Mt. St. Helens, MX and Minuteman site tests again should be best estimates as to distribution, with one or two concentrations used, and again with temperatures (A) selected as a result of former tests. Indeed, all tests following the exploratory "I" tests should have parameters based on careful considerations of prior results. Therefore, the number of test runs are as follows:

I	(1)	9 (3 x 3 temperature choice)
	(2)	4 (2 x 2 temperature choice)
	(3)	4 (2 x 2 temperature choice)
II	(1)	2 to 4
	(2)	2 to 4
	(3)	2 to 4
TOTAL:		23 to 29

Each test should take less than an hour of actual running time, in fact, a few minutes would be sufficient to indicate the severity of glassification. If any further tests are required to quantify the glassification problems, then implementation of such tests would require further discussion and amplification. It is important to outline a logical procedure that can be cut off or expanded conveniently as required by the ongoing results.

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Appendix A

MISCELLANEOUS DOCUMENTATION OF THE MT. ST. HELENS/C-130 INCIDENT

ASSEMBLED BY:

DEANE OBERSTE-LEHN (CONSULTANT)
J.F.W. PARRY

[redacted]

08 May 1980

RE: L-100 MT. ST. HELENS INCIDENT

Telecon's with Tony Anderson (National Airmotive) 415-635-1500 and Ross Carruthers, Power Plant Engineer (Trans America Airlines) 415-577-6231.

Engines stripped and examined by National Airmotive. No formal report issued but we will be send photographs and data that were sent to Trans America. Hardware has been scrapped.

1. All four engines damaged - only one was able to be recovered.

2. Deposits (as previously described) mainly on nozzle guide vane leading edge (pressure side) and thermocouple holes plugged.

3. Severe scoring of compressor casing (aluminum) and compressor blade erosion.

4. Much dust and debris throughout engine and air ducting.

5. No oil contamination.

6. No aircraft damage.

Frank Parry

[redacted]

AC No. 43-16

General Aviation airworthiness ALERTS

SPECIAL ISSUE

VOLCANIC ASH HAZARD!

AIR CARRIER
&
GENERAL AVIATION

U.S. DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration
Flight Standards National Field Office

[redacted]

1. Introduction. The purpose of this special alert is to provide safety information and recommended actions to preclude possible airworthiness problems associated with aircraft exposure to volcanic ash either in the atmosphere or on the ground. The following recommendations are based on the best available information at this time and will be amended as further information and facts are gathered.

2. Background. Volcanic ash from Mount St. Helens has been analyzed to contain abrasive and corrosive materials such as sulfuric acid and flouride and chloride salts and acids. Depending on the location of the volcanic ash fallout, the particle sizes range from as small as .5 microns to 100 microns. Most aircraft screens will filter out material down to 15 microns but will pass particles that are smaller.

The ash will probably be encountered as a fine powder, like talcum powder, light grey in color. When dampened it has been reported to set similar to concrete. Due to adhesive action of the sulfuric acid, the acid tends to adhere to the interface between the particles and the aircraft structure causing corrosion. Although volcanic ash may not be visible on the structure, sulfuric acid may still exist causing corrosion and it is recommended that all aircraft that have been exposed to volcanic fallout be given a test to determine the acidity levels. This can be accomplished by the application of nitrazine paper available from many pharmacies. If the Ph factor is 4 or below, it is recommended that the following corrective actions be taken as soon as practicable.

3. Airframe.

(1) Safety precautions including safety glasses, gloves and protective clothing should be adhered to.

(2) Aircraft should be cleaned in the following sequence:

a. The aircraft manufacturer's maintenance manuals should be followed regarding the protection of aircraft systems during the cleaning process. The procedures recommended by the manufactuere for the inspection and cleaning or purging of pitot static systems, instruments systems, etc., should be followed.

b. If there is any volcanic ash coating on the aircraft structure, it should be removed by hand brushing, air or vacuum cleaning prior to performing any washing actions. If the aircraft is washed before removing ash, it will form a corrosive paste.

c. The aircraft should be thoroughly cleaned, inside and out, before washing.

d. The aircraft should be rinsed thoroughly with fresh water without scrubbing to ensure that all parts of the aircraft have been amply rinsed.

e. The aircraft should be given a test at the completion of each wash cycle to ensure a Ph factor of above 4. The Ph factor may be performed by taping nitrazine paper strips on various parts of the structure and wetting with distilled water.

f. It may be necessary to repeat the wash procedures on a continuous basis in areas where fallout continues. To ensure that the sulfuric acid is neutralized, complete the wash cycle using a petroleum base solvent.

g. It is recommended that regardless of the Ph factor, aircraft exposed to volcanic ash be given a water wash as assurance against corrosion.

h. Close inspection for external signs of damaged seals, especially landing gear and landing gear actuators.

4. Systems. For all aircraft exposed to volcanic ash on the ground or air, system checks should include inspection of pitot-static probes, static ports, air conditioning outflow valves and filters, generator cooling tubes and filters, vacuum lines and filters, and externally mounted sensors, such as long wire antenna, and angle-of-attack sensors, to remove any ash contamination. Precautionary inspection should be done on a random basis of electronic equipment subject to cooling air to assure need for equipment removal of ash contamination.

5. Powerplant Considerations.

(1) General. As noted above the nature of the volcanic ash is that it is both abrasive (in the form of fine powder) and corrosive (in the form of acid content). Both turbine engines and reciprocating engines may be affected. Compressor and turbine blades suffer erosion by abrasive particle impact. Lubrication and other fluid systems are subject to contamination by solids and chemicals, while moving parts are subject to abrasive wear.

The abrasive nature of the material causes rapid mechnical damage to moving parts. Experience has shown that engines operated with oil contaminated with the ash has caused them to fail in as few as 20 hours after exposure.

The acids associated with the ash are soluble in oils and as such attack engine parts resulting in rapid deterioration. Engines can also be attacked externally by the corrosive action.

(2) Maintenance. Engines which have been operated or subjected to a volcanic ash fallout need:

a. Thorough external cleaning.

b. Cleaning or changing of all oil, fuel, and other systems screens and/or filters and draining all sumps. Flushing and cleaning of

contaminated fluid systems should be accomplished following the engine manufacturer's recommended procedures.

c. Cleaning and scavenging of any open tanks where the ash or chemical action could collect and concentrate.

d. Oil and fluid draining and change.

e. Close inspection for external signs of damaged seals.

f. Cleaning and inspection of accessories and components for contamination such as vacuum filters and regulators.

g. Following cleaning, inspection, and fluid changes the proper operation of the engine should be verified by run-up. Frequent oil and fluid changes should be scheduled. During subsequent operation temperatures and pressures should be monitored closely for changes which may signal problems.

h. Spectrographic oil analysis is an indicator of engine wear and contamination. Comparison of analysis of early samples after cleaning with previous analysis reports can serve as an indicator of an engine's stability.

6. Recurrent Inspections. Aircraft owners and operators are urged to closely monitor aircraft and engines, including systems, on a continuing basis and take action as deemed necessary for aircraft exposed to volcanic ash as assurance against corrosion.

May 21, 1980

A Transamerica Con [illegible]

CONFIDENTIAL

To: All Pilots *Date:* 5/23/80

From: H. L. Babcock

Subject: Volcanic Ash Hazard

The attached advisory circular about the volcanic ash hazard is primarily intended for Maintenance. However, it does have some interesting notes that will provide background material for you relative to the recent volcanic difficulties in the Northwestern U.S.

HLB:ljc

CONFIDENTIAL

[illegible]

MIN/SEC

CAPT. Seattle Center Transamerica 24 59210 Altimeter 3.5 — 0:6

ATC. Check that 24 Seattle Center. Roger and a flight heading 170 be a vector little bit west of St. Helens, or unless you want to, you can fly 160 and to Portland here in about another 20 miles, over.

CAPT. Whatever, I don't know how. . .at this. . .we're going to a 170 be okay.

ATC. Check that 24, roger. If it looks like you're getting into that fall out at all, you can deviate further West if you like, over.

CAPT. Okay.

ATC. Transamerica 24, You notice any clouds at all, or just regular weather clouds? — 4:35

CAPT. It appears to be just regular weather clouds. We're broke out in a layer in about 7, went back in and out again at about 9, and we're in again now. I don't know whether to. . .I don't smell anything, so I don't know exactly what to expect, but we're still on restricted visibility.

ATC. Ok, thank you. Let me know if you break out again. OK?

CAPT. Ok.

CAPT. Center Logair 24, we broke in between layers again at ah about 11.5 — 5:30

ATC. Ok. You say you're in the clear at 115?

CAPT. Yeah, it looks like another layer above and ah, it looks kind of murky and gray, and it's blue to the East.

ATC. Ok. It's blue to the East, is it?

CAPT. Yeah, it looks like it's in between layers.

ATC. Ok. Fine. Do you want to deviate any? I can approve it to the West, probably, if you like. What's your visibility like now?

CAPT. Oh, we got good visibility here now, but we appear to be between layers. — 6:10

ATC. Thank you.

CAPT. And we're back in at about 12.7 — 6:45

ATC. Thank you.

CAPT. AF Center Logair 24, we're at 13.5 right now between layers and it looks like some big cloud ahead of us and it goes way up. — 7:32

ATC. Ok. Does that look like it's extremely dark--like a volcanic cloud, or just a typical weather cloud?

CAPT. No. It looks like more a volcanic cloud. It looks like. . . grayish. . .well, when the sun was shining on it a little bit this morning, but it does not look like a regular cloud so much.

ATC. Ok. Are you going to clear it on your present track, or do you want to go out to the West more?

CAPT. We'd better go out to the West some more, and we just. . .I don't know if we got any lightning in this area, but we just had a flash of what appeared to be lightning, or is seems to be more reddish. I don't know.

ATC. Ok. Transamerica 24, stay clear of the cloud, and there has been a lot of lightning. It's associated with those clouds and coming out of it.

CAPT. Yeah, roger. We're going to turn to the West because we're beginning to smell it now.

ATC. Ok, sir. Take whatever action you need to stay clear of it.

CAPT. Roger. 8:40

ATC. And can you approve a. . .maintain VFR out West now at all?

CAPT. Ah, I don't believe so at the moment.

ATC. Ok, if you want to 180 or whatever to get out of it, that's fine.

CAPT. We're turning out to a Westbound heading and see what happens.

ATC. Roger.

ATC. Transamerica 24, let me know, if you will, as to how far West possibly we would have to keep traffic in order to stay clear of that, if you can. 9:15

CAPT. Roger.

ATC. Did it look like you were going to stay beneath it here up til about 15th or so?

CAPT. Well, we were in and out of clouds up to about 15.

ATC. Roger. Can you still smell it now?

CAPT. Yeah, we can still smell it and it's pretty dark out here. 9:55

ATC. Transamerica 24, do you have radar?

CAPT. Roger, but I don't have it turned on.

ATC. Ok, I show an area clearing. You're entering into it now, but I show some weather in about 10-12 miles, a heavier build up, and I don't know whether that's just a blind spot in my radar, or whether it's a natural build up of weather ahead of you.

CAPT. Roger. Evidently that cloud must be moving West bound, because we seem to be. . .We're still in it and it seems to be as bad, or worse now than it was before. 11:16

ATC. Ok, sir. Thank you.

ATC. Can't talk you into any suggestions other than you'd probably get out of it, I suppose, South bound. I can't really tell you how far it would take to go.

CAPT. Roger. We're going to turn back north bound. We're going to a. . .we just lost an engine here. 11:44

ATC. Roger, sir. Ok, McChord's at you. . .just about 330 at about 135 miles.

ATC. Transamerica 24, do you want to go back to McChord?

CAPT. That's affirmative.

ATC. Ok.

CAPT. And we're gonna. . .ok, listen. We lost number 2, and we started to descend. 12:28

ATC. Ok, sir. I've got no traffic at all; you can descend on down to as low as 5000' at this time.

CAPT. Roger, thank you.

ATC. Transamerica 24, do you want to vector into McChord, or do you want to provide your own? Over.

CAPT. McChord. Let down for landing. 13:20

ATC. Transamerica 24, I got your answer. Heading to McChord, 360. Over.

CAPT. Ok, we're going a little bit east further here. Ok, we can round 360 now.

ATC. Transamerica 24, roger. Transamerica 24, how many souls on board, and also, a fuel on landing if you can?

CAPT. We got about 18,000 of fuel. We got three people on board. 13:55

ATC. Transamerica 24, roger. Number 2 is the only one down?

CAPT. No, we got No. 2 and No. 4 out right now.

ATC. Roger.

ATC. How about Olympia Airport. It's at your 10 o'clock at about 12, 13 miles. 14:05

CAPT. Roger.

ATC. It's actually 21 miles.

ATC. Transamerica 24, do you want to consider Olympia Airport? Over.

CAPT. Say again please.

ATC. Transamerica 24, roger. I say again. Olympia Airport is at your 10 o'clock by 20 miles. McChord would be at 11 o'clock by about 33 miles.

CAPT. No. I think McChord's alright. We got to start letting down here some if we can.

ATC. Transamerica 24, roger.

CAPT. Ok. We're heading on 360. Over.

ATC. Transamerica 24, roger.

ATC. Transamerica 24, McChord would be bearing 356, 31 miles contact SEA approach now 119.5.

CAPT. Roger, 119.5 and safely we could go down to. . .

ATC. 5000' sir.

CAPT. Ok. 15:20

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PILOT OPERATIONS BULLETIN 80-003 May 29, 1980

AIRCRAFT ENCOUNTER WITH AIRBORNE
PARTICALS OF VOLCANIC ASH

On the 25th of May, this year, Transamerica Airlines Flight 222/146, an L-382, operating between McChord Air Force Base and Travis Air Force Base, encountered a volcanic ash cloud produced by an eruption from Mount St. Helens in southwestern Washington. The flight departed McChord at 1137Z and was cleared to operate direct to PDX then Jet 1 southbound to KSUU. Flight conditions were in and out of cloud layers during the climb, and the flight was operated essentially during darkness, although it was beginning to become light. At approximately 16,000', Captain E. Tripp notified ATC that he had an unusual smell in the cockpit, that he was in IFR conditions, and that he thought the problem could be attributed to volcanic ash. ATC acknowledged the report and provided the aircraft with a radar vector to turn right to a heading of 270°—such heading designed to take him away from the volcanic area.

Shortly thereafter, approximately 2 or 3 minutes, #4 engine began to stall, surge, and generate what the Captain described as a back fire. The engine operation became uncontrollable and it was necessary to shut the engine down (feather). This occurred at 1153Z. At approximately 1155Z, #2 engine suffered the same type of failure, and Captain Tripp was forced to shut down that engine. Captain Tripp subsequently notified ATC of the engine failures and informed ATC that he was turning north and descending. Captain Tripp elected to return to McChord, which he felt was the best procedure, primarily due to his current knowledge of the local weather conditions at McChord, the long runway, and available emergency equipment. Captain Tripp indicated that the remainder of the trip was uneventful.

For general information, the location of the St. Helens Volcano is East of and immediately adjacent to Jet 1 (14 NM) between Seattle and Portland. The volcanic eruption of St. Helens had occurred approximately 1½ hours prior to the departure of Flight 222/146 from McChord Air Force Base. There were no cautionary notams in effect with regard to the volcanic eruption, and ATC had provided no information to our flight with regard to routing the aircraft away from the volcano. The only report we have been able to find on the ash cloud that was issued prior to the departure of our aircraft, was a sequence report from PDX flight service station, indicating that radar had observed an ash cloud at 14,000' drifting northwest. The information, therefore, apparently was in the ATC System, but cautionary notams had not been issued.

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[redacted]

Subsequent to the [redacted] ATC issued a notam at approximately 1230Z closing a large area of Northwest Oregon to aircraft operations from sea level to 40,000'. The area encompassed by this enclosure can be defined by a line running from Portland to Yakimah, to Olympia, to Neah Bay to Portland.

An inspection of the aircraft after its arrival at McChord indicated that engine 2 and 4 had sufferred compressor errosion and severe turbine damage, engine 3 had sufferred turbine damage also. All three forward windshields sufferred severe abrasion and required replacement. Numerous components of the air conditioning system also required replacement. Additional remarks made by the operating crew indicated that ash concentrations reduced the visibility in the cockpit.

We thought that this volcanic ash encounter would be of interest to all pilots regardless of the type of aircraft you are assigned to. We do, however, plan to provide a more detailed report to L-382 crewmembers. This bulletin is for information only and need not be retained.

E. L. Babcock
DIRECTOR, FLIGHT SYSTEMS

ELB:ljc

[redacted]

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Transamerica Airlines
P.O. Box 2504
[redacted]

To: H. L. Neff *Date:* 5/30/80

From: H. L. Babcock

Subject: Preliminary Report on the Encounter with Volcanic Ash of Aircraft 24ST on 25 May 1980

The flight crew consisted of Captain Tripp, First Officer Bowcock, and Flight Engineer Salmon.

VOLCANO ERRUPTION

At present, we have received various estimates of the volcanic erruption time. The most recent, and we believe the most accurate, was that the initial erruption occurred at 0952Z, and that a subsequent major erruption occurred at approximately 1100Z. We have yet to confirm these items with the U.S. Forrest Service, but we will do so.

FAA NOTAMS

The earliest notams that we can find, at the present time, although we are still researching this with the Weather Bureau in Redwood City, is that at approximately 1245Z on the 25th, the FAA issued numerous subsequent notams outlining an area where flight operations would be restricted and periodically enlarged this area as the volcanic ash drifted northwest. It may be of interest to note that we have a Weather Bureau sequence report issued by Portland on the 25th at 1103Z which indicates that radar was able to establish the presence of an ash cloud at 14,000' drifting northwest. It is unlikely that this sequence report would have been available to the crew prior to their leaving McChord.

AIRCRAFT OPERATING TIMES

24ST departed SUU for TCM at 0829/33Z
Arrived TCM 1048/51Z
Departed TCM 1130/37Z
Arrived TCM 1214/21Z

The ash encounter occurred at approximately 1153Z at which time #4 Engine was shut down.

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The major erruption of Mt. St. Helens Volcano occurred at 0930Z on Sunday May 25th, 1980. Steam and ash emission to 24,000' and building. At approximately 0944 ash clouds drifted as high as 25,000' and the highest and last reading was taken at 26,000'.

Information received from the U.S. Forrest Service Information Center, Seattle, Washington.

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[redacted]

ATC RECORDING

Mr. Jim Litzen of Seattle ARTCC and Mr. Arnie Guadaluppi of the FAA have been contacted with regard to the communications conducted with our aircraft by the Seattle center and by approach and departure control from McChord. We have been advised that the recordings will be forthcoming, but we do not have them at this time. The principal notam in the force at the time of the eruption, according to Mr. Litzen, was that aircraft would be vectored at least 20 miles away from the Mt. St. Helens Volcano.

AIRCRAFT VOICE RECORDER

The Aircraft Voice Recorder was received yesterday afternoon, May 29, and a cassette tape copy of the voice recorder will be available at approximately 2:00 pm on the 30th. The items attached to this report are originals and/or copies of the following:

1. Captain Report
2. Flight Engineers Report
3. FAA FSS Sequence Reports
4. Military Airport Weather Reports
5. Flight Plan for 24ST — DD175
6. Flight Release
7. Aircraft Log Book Pages
8. Military Weather Briefing Form
9. McChord AFB Terminal Weather Record
10. FAA Notams
11. Operations Control Log
12. Pilot Operating Bulletin, describing the volcanic ash encounter

The description of the incident is essentially the same as that prepared for the Pilots Operations Bulletin 80-003 and contains all pertinent information available at this moment. Captain Tripp's flight was filed via Jet 1 PDX direct to McChord. Such a track would take him approximately 16 miles west of St. Helens. However, radar vectors would normally be applied to the track of the aircraft between PDX and KTCM.

HLB:ljc

[redacted]

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General Offices: (415) 577-6000

ORIGINAL WRITTEN REPORT BY CAPTAIN E. TRIPP

Quicktrans 222 - 24ST

1. Normal departure time.

2. Reported cloud layers at approximately 7000', 9500' and 13,500'.

3. Began to smell ash shortly after while climbing. At approximately 15,000 to 16,000 ft., it began to get darker and smell stronger. ATC suggested a turn to the west (270°).

4. Within a few minutes, #4 engine began to backfire, torque and fuel flow were fluctuating, and the power was uncontrollable. We shut down #4 engine closely followed by #2 engine. We turned back to the North and started decent. We became clear of the ash cloud shortly after.

5. Decided to continue back to TCM. The weather there was good on departure and straight in let down on ILS seemed to be the best procedure. Aslo, a long runway and good emergency equipment was available.

lc/

[redacted]

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24 ST F/E SALMON VERBAL REPORT
As Received by Chief F/E C. Reber

During climb, entered smoke cloud, cockpit became very dark. About 12 minutes after takeoff, climbing through 12-13,000 ft. on a heading of 190°, there was a smell in the cockpit line welding, or hot metal— in a mist like rain. Climb power, all engines normal. The smell became stronger and #4 engine made a back fire noise approximately four or five times.

The cockpit was very dark and explosions, reflecting from the clouds, lite up very bright. All engine instruments were fluctuating, and #4 engine was shut down with condition lever. No fire or overheat warning lights were on.

During cleanup, Check list #2 identical, but not as severe. At this time, the #2 parallel light came on. High F/F, low TIT. Condition lever shut down. Now, at 17,000 ft. and heading 270°.

Power on #1 and #3 was reduced, and several 360° turns made to final approach. Aircraft weight was 119,000 and fuel 18,000 lbs.

Parking is at the end of the runway, therefore, there was very little taxi time to get engine readings. The aircraft had to be moved, but no tow bar. Number 1 and 3 started, and the aircraft taxied 2-300 yeards and turned heading toward the runway. During the taxi, both engines were in normal high speed idle—TIT 350°. F/F, as best remembered, were normal at about 600 PPH.

During the engine inspection, #4 turbine blades were missing, approximately ¼" off all tips and #2 missing 1/8". Blades were blue and black in color, as were the tail pipes. The bottom of the tail pipes had about a cup full of black shiny grains in the size of fine sand to small peas. Number 1 and 3 turbines and tail pipes are like new. Compressors on all are very clean. The inside of the cowlings were covered with fine sand/dust, as was the inside of the cockpit.

A written report from Flight Engineer Salmon will follow.

CAR:ljc

[redacted]

L. A. Miller September 10, 1980

H. L. Babcock

24ST - Encounter with Volcanic Ash - 25 May 1980

You and Mr. Riley have asked me for my personal opinion as to any responsibility that ATC may have had relative to this encounter. You have available in your file my letter of May 30, 1980 on this subject and the written report, or copies thereof, of the Captain and Flight Engineer operating this flight. The question seems to be, did Captain Tripp and his crew have advance notice of the situation in the form of notams or other aeronautical advisories and, if they did not have these, did this in any way jeopardize the flight through the lack of information. In the effort to resolve these questions I contacted Captain Tripp by telephone on Wednesday, September 3 and have also generated a written request for him to provide some specific responses to questions that could hopefully shed some light on this matter. (I have attached a copy of that letter to this correspondence.)

Since I have not received an answer from Captain Tripp in writing as yet I will attempt to paraphrase his verbal response to these questions.

Q. Was Captain Tripp aware of the eruption prior to his departure from McChord Air Force Base southbound?

A. Captain Tripp indicated that the eruption occurred while they were airborne from Travis AFB to McChord AFB while they were still at cruise altitude, prior to descent. ATC notified the aircraft of the eruption by radio almost immediately after its occurrence. Captain Tripp indicated that there was no difficulty with ash encounter from the eruption on his descent and arrival into McChord. Since he had received considerable advisories directly from ATC on the eruption during his arrival, he did not review the situation with McChord AFB weather office. He and his crew, however, were aware of the volcanic situation prior to his departure from McChord.

Seattle Center was contacted, as you know, subsequent to the incident and we requested transcriptions of all the appropriate transmissions between ATC and 24ST (since there had been some rumors that ATC had allowed, or vectored, our aircraft into an ash situation, a request was made for all pertinent notams on the subject). The Seattle FAA was quite cooperative and provided us with a tape recording of the conversation between 24ST and Seattle Center which we have transcribed. The transcription indicates that Captain Tripp received complete cooperation from ATC in his attempt to avoid an ash encounter and there is no apparent indication that ATC is responsible for directing the aircraft into the ash area. Captain Tripp also indicates that ATC cooperated in every way possible to assist them in avoiding the ash. Captain Tripp also indicated in our phone conversation that, afterhe had landed at McChord and was in the hotel, the ATC called him to discuss his problems. During this conversation, the ATC representative indicated that they had very little to go on in terms of radar echos as an indication of any ash and, of course, since the aircraft had lost two engines and provided ATC with a bona fide emergency that was handled successfully by both the pilot and ATC, they were certainly interested in discussing the incident directly with the Captain.

Captain Tripp has a copy of the transcript that we generated from the ATC tape and has indicated that, as far as he can tell, it is an accurate description of the communication during and after the incident.

Q. Was the radar used during this departure?

A. Captain Tripp indicated that the weather conditions that existed during his arrival were primarily stratified layers with clouds at the lower altitudes (below 15,000') and light rain in progress in the Seattle area. There was no need for any radar since there was no indications of any meteological conditions that would have generated turbulence. He therefore elected not to use radar on his departure from McChord.

Some question has been made as to whether or not the radar could have been used to identify the ash clouds and thereby allow the pilot to avoid an ash encounter. It should be noted that there is no definitive background on which to base such an assumption and the radar reflectivity of volcanic ash as received by an airborne receiver was unknown at the time of the incident and, for that matter, is still unknown. The fact that Captain Tripp did not utilize the radar on this flight would not, in my opinion, jeopardize the aircraft since little useful information would have been available with the radar operating.

There is some indication that radar can identify ash cloud activity in certain occasions and we have at least one report in the weather data that was forwarded to us, that the Portland flight service station noted an ash cloud on radar prior to Captain Tripp's departure from McChord. (This report is included in the file.)

The effect of airborne volcanic ash on aircraft has been documented somewhat by various notams and bulletins produced after the original eruption on May 18 of Mount Saint Helens by the FAA and the weather bureau and the Boeing Company. However, they do not indicate that it would jeopardize a large turbine aircraft to the extent that occurred in this incident and, therefore, both Captain Tripp and ATC were unaware, I believe, of the serious consequences that were possible as a result of an ash encounter. Also, there is some evidence that the material we encountered was something more than just ash. In fact, the Maintenance Department had identified the material verbally as "powdered granite".

In summary, with the available information to date received by this office and the conversation with Captain Tripp and the transcript between our aircraft and ATC, there is no indication, in my opinion, that ATC could be culpable in this instance. This is not a legal opinion but merely a practical opinion of my review of the available data.

ELB:lck

[redacted]

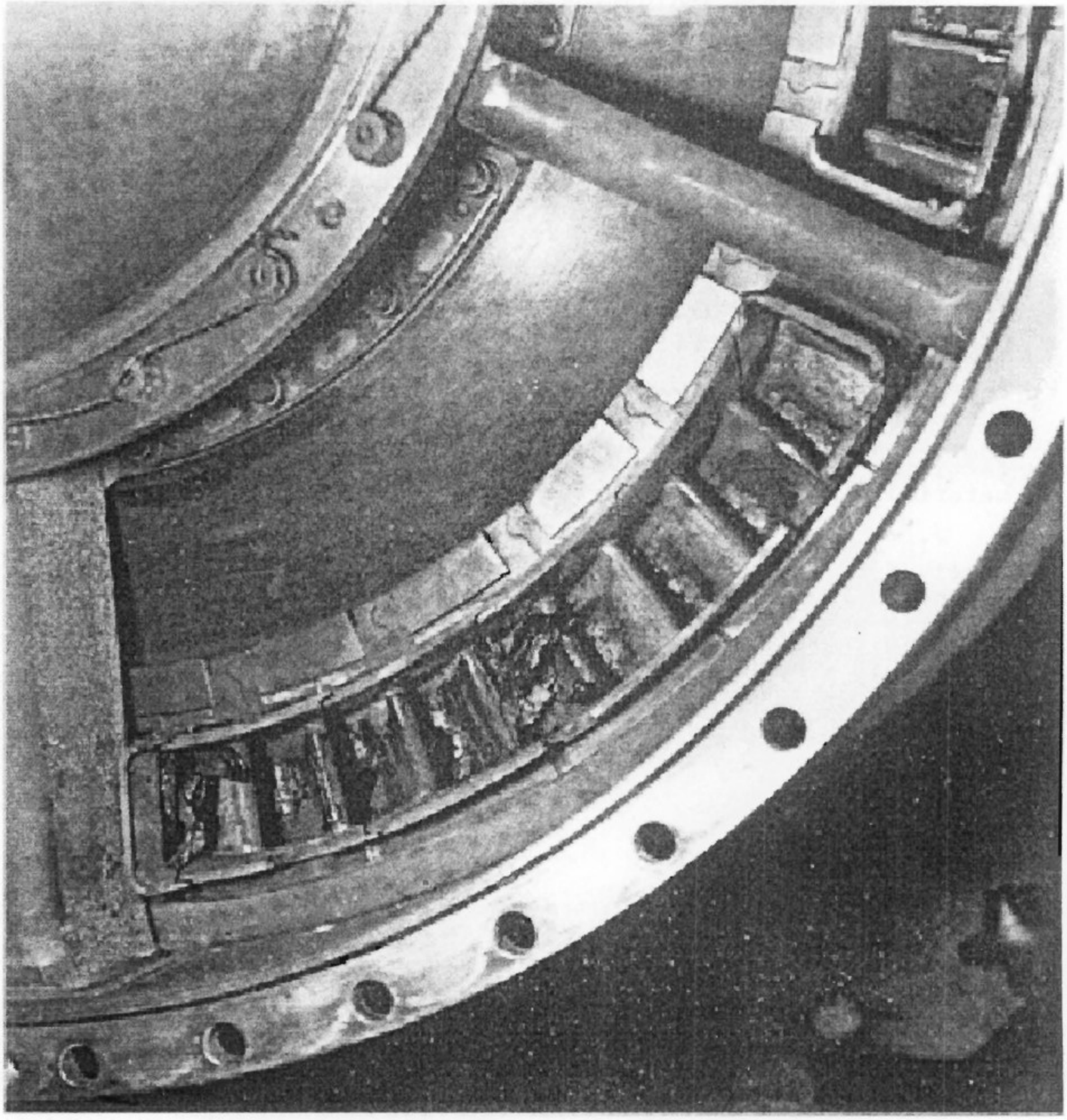

Figure A1. First-stage stators.

[redacted]

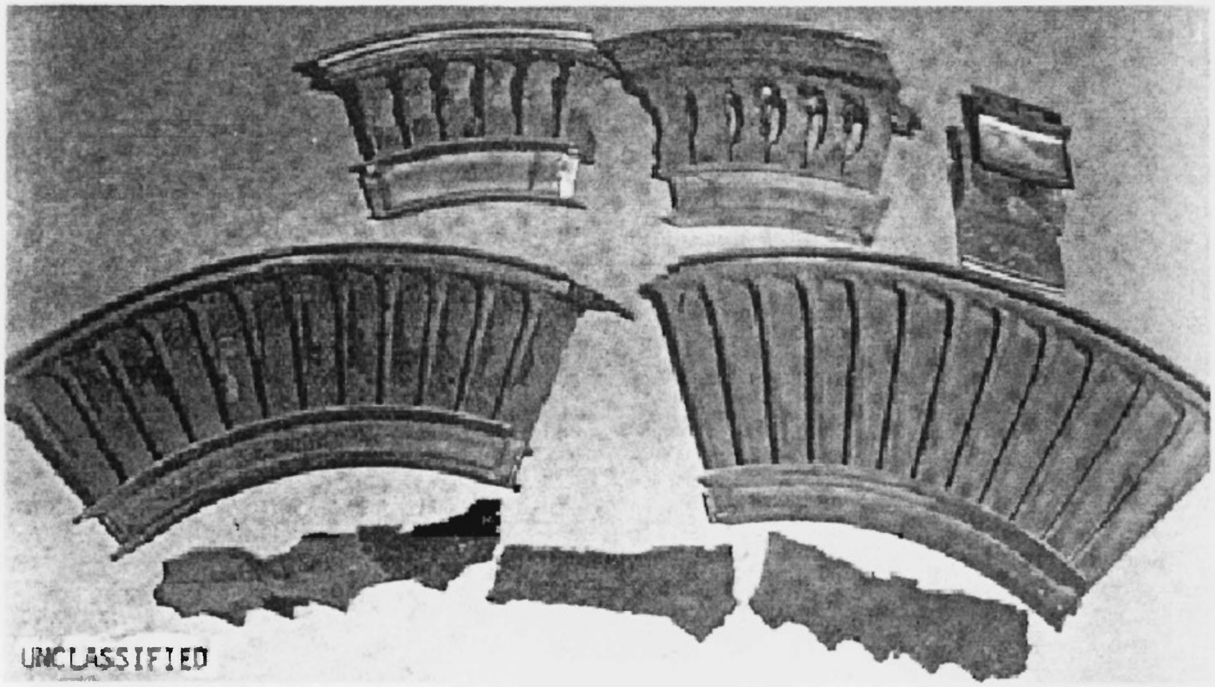

Figure A2. Portions of turbine stators, first through fourth stages.

[redacted]

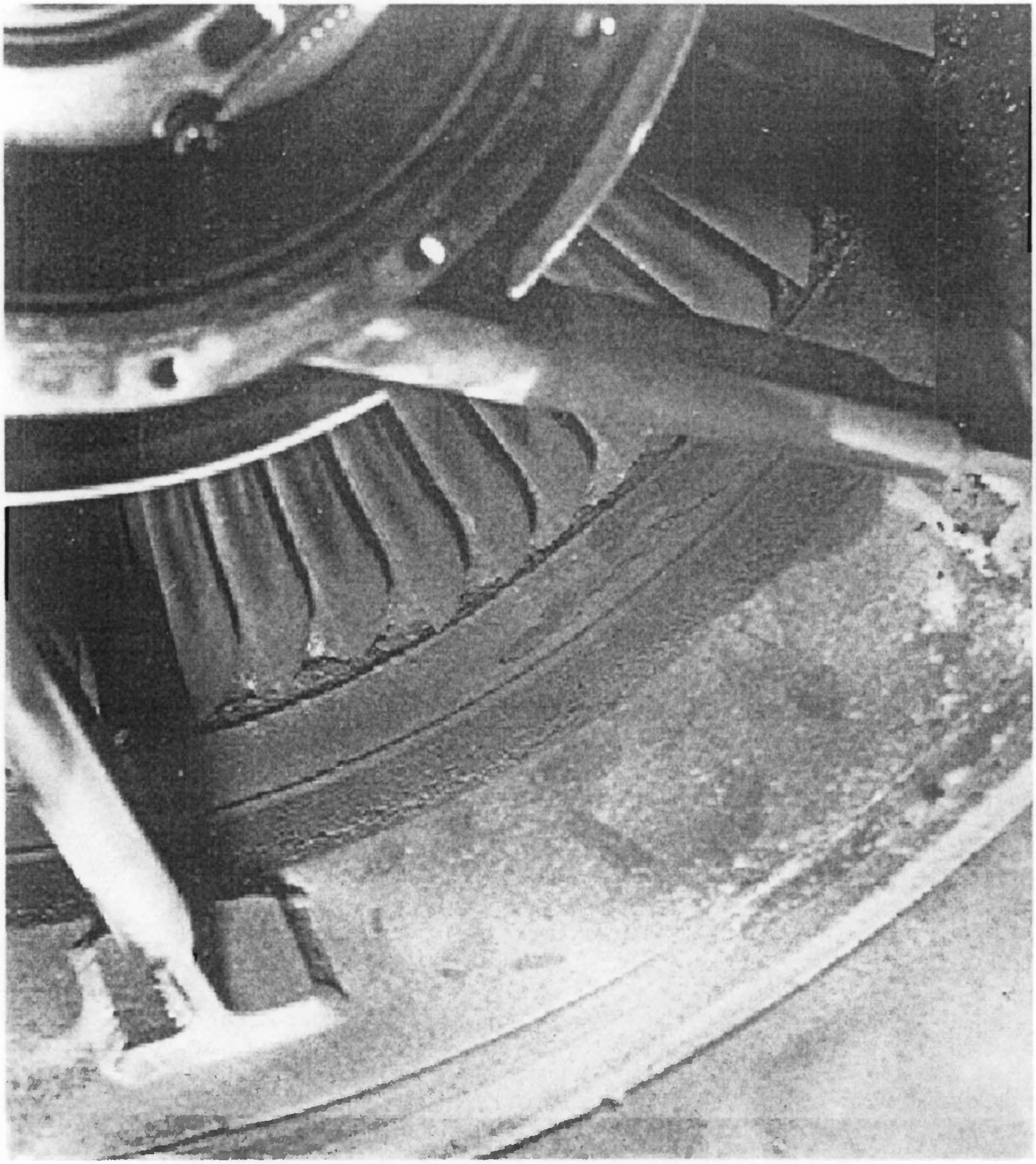

Figure A3. Turbine blades and housing.

Figure A3. Turbine blades and housing

[redacted]

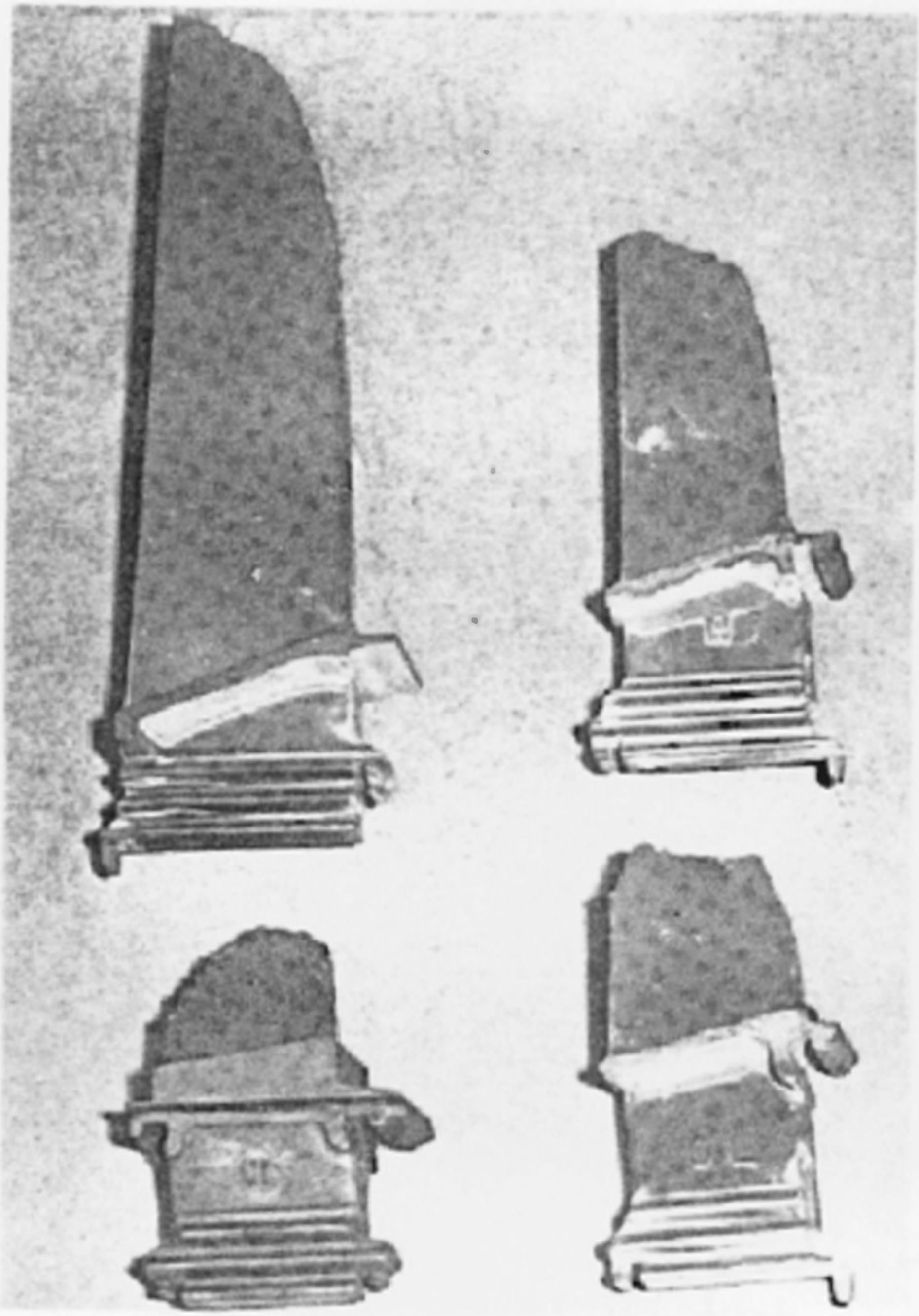

Figure A4. Turbine blades, first through fourth stages.

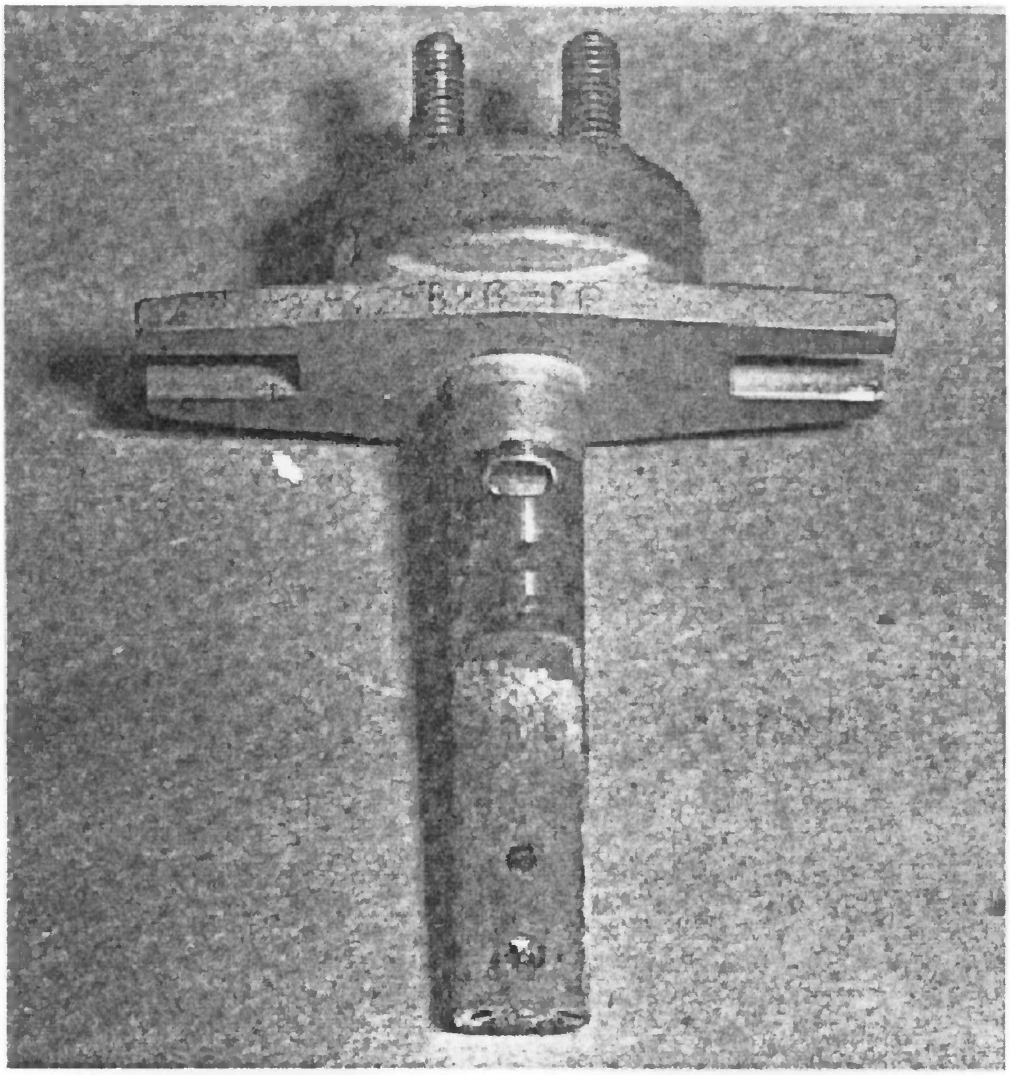

Figure A5. Turbine temperature probe.

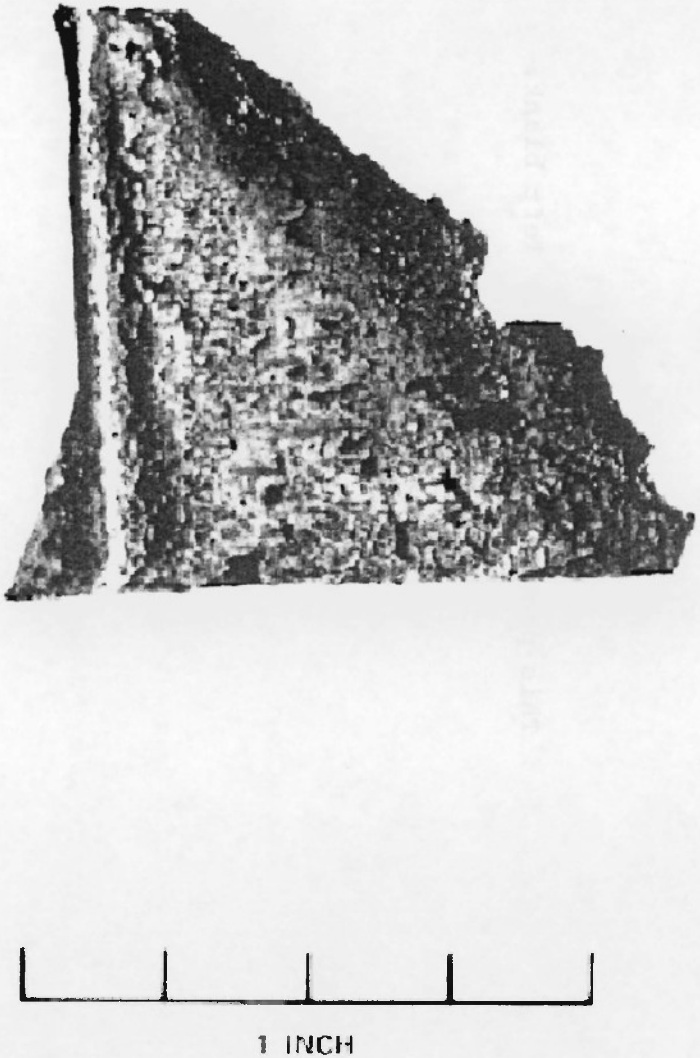

Figure A6. Glasslike deposits on stator blade.

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ANALYSIS OF VOLCANIC ASH SAMPLE--MT. ST. HELENS

J. Shigley and G. Brown, Jr.
Department of Geology
Stanford University

[redacted]

ANALYSIS OF VOLCANIC ASH SAMPLE - MOUNT ST. HELENS

This report summarizes the mineralogical and chemical characterization of an ash sample from the 25 May 1980 eruption of Mount St. Helens following the instructions of Dr. Deane Oberste-Lehn. This sample was collected from a jet engine on a C130 aircraft which had been flying in the area on the day of the eruption and was accidentally caught in the ash cloud. The exact location in the engine from where the sample was taken is not known, but presumably the material was removed from near the front turbine blades.

Various techniques were used to mineralogically characterize the ash. These techniques, which included optical and x-ray methods, are the standard procedures employed in the analysis of other geologic materials.

Several portions of the ash were first examined optically under a reflecting microscope to determine particle size and shape. Grain sizes were quite consistent from one grain to the next, and fell within a range of 0.50 - 0.05 mm. Most grains had diameters nearer to the lower end of this range, so that the average grain size was approximately 0.10 mm. Volcanic ash of this type can be described as being fine-grained and well sorted.

The shape of individual grains was found to be somewhat dependent on their nature. Most grains were irregular in shape although roughly equidimensional, had an angular or subangular outer surface, and appeared to represent fragments of larger grains of minerals or rocks. A 10 - 20% fraction of the sample consisted of portions or entire single crystals which had euhedral outlines (outer surfaces consisting of flat crystal faces). In such instances; these crystals often were elongate in one dimension.

Under a transmitting light microscope, most grains were found to be individual minerals, as opposed to a smaller fraction (10-20%) of rock fragments (aggregates of two or more minerals). Mineral grains could be recognized by their internal homogenity, uniform color, and regular shape. Rock fragments were distinguished by nonhomogenity, variable color and texture, irregular shape, and were composed of several identifiable mineral fragments. On the basis of their optical character, a small percentage of grains appeared to be glass fragments, but the amount of these grains could be incorrect since they looked much like some of the clear mineral fragments and could only be distinguished under cross polarized light. A rough visual estimate of grain proportions from several portions gives the following volume percentages:

clear mineral grains - 55%	opaque grains - 5%
green/brown minerals - 15%	rock fragments - 20%
glassy fragments - 5%	

Determination of the mineral content of the ash would be an important part of an analysis of this kind, since knowledge of this information would permit the use of existing data on the physical properties of these minerals. Mineral identification was performed using standard optical

and x-ray methods. A small fraction of the sample was placed in a drop of refractive index oil and examined under the microscope. On the basis of their optical properties, the clear glassy minerals were found to be feldspars, while the green and brown grains turned out mostly to be pyroxenes- both common groups of silicate minerals in volcanic rocks. The dark or opaque grains were either rock fragments or minerals such as magnetite (which could be removed with a steel probe due to its magnetic properties).

Confirmation of this preliminary assessment of ash mineralogy came from the x-ray diffraction pattern. A portion of the sample, from which all visible engine fragments had been removed by hand picking, was ground under acetone in an agate mortar. This powder was spread on a glass slide and run on a Philips-Norelco x-ray diffractometer using Cu K alpha radiation. X-ray diffraction data were collected over an angular range of 5 - 60 degrees 2 theta. As shown on the attached pattern, the resultant x-ray diffraction peaks, from whose location the minerals present in the sample could be identified, were found to be sharp and clearly defined. This sharpness indicates that the minerals in the ash were crystalline, and apparently had not been subjected to physical conditions which would have destroyed their internal crystal structures. Broad, poorly resolved peaks indicative of non-crystalline glassy material were not found in the diffraction pattern. Presence of the following minerals is indicated by x-ray data, although a check was made on the x-ray pattern for a much larger group of potential minerals.

Mineral	Chemical Formula	Hardness	Melting point
Plagioclase Feldspar	$NaAlSi_3O_8$ - $CaAl_2Si_2O_8$	6	1100-1500 °C

(this group represents a complete range of minerals between a calcium end member anorthite (An) and a sodium end member albite (Ab). Approximate composition of this mineral in the ash is $Ab_{90}An_{10}$ - $Ab_{50}An_{50}$)

Mineral	Chemical Formula	Hardness	Melting point
Hypersthene (pyroxene)	$(Mg,Fe)SiO_3$	5-6	1300-1400 °C
Sanidine Feldspar (?)	$KAlSi_3O_8$	6	1300-1400 °C

(the presence of this mineral was suspected from the optical examination, but could not be distinguished from the x-ray pattern because its major peaks roughly coincide with those of plagioclase)

Additional minerals could be present in smaller amounts (such as magnetite, biotite, or tridymite), but if a mineral is present in quantities less than about 5%, in most instances its x-ray peaks would be of insufficient intensity to appear above the background level on a diffraction pattern.

Silicate minerals such as those listed above are known to begin to crystallize over a range of 1100-1500 °C in volcanic magmas. Under the microscope, none of the ash grains exhibited any visual indication of complete or even partial melting (with the exception of the few glass fragments which probably were present in the ash cloud itself). All grains appeared quite fresh and were apparently unaffected by the temperatures existing in the portion of the aircraft engine where they had become lodged.

In order to obtain some indication of the melting points of the ash constituents, a portion of the sample was heated in a platinum crucible in a Deltec furnace. Initial heating at 900°C under atmospheric conditions was performed for some 30 minutes, and then the crucible was withdrawn from the furnace and quenched by partial submergence in water. A careful examination of the contents was then made under the microscope to check for melting. If no changes were observed, the crucible was reinserted into the furnace and heated at 1000°C for 30 minutes. Subsequent 30 minute heatings at 100° increasing increments were continued until the sample melted. Nothing was noted until after the 1100°C stage, when some of the grains were found to adhere slightly to the crucible. After 1200°C, partial melting was clearly visible. Most of the clear feldspar grains were found to be sitting in droplets of glassy material. The darker pyroxene grains did not appear to be affected. Upon reaching 1300°C, only a few of the dark grains remained as distinct fragments - all other grains were completely melted. Total melting of the sample occurred after 30 minutes at 1400°C.

In order to obtain some semiquantitative information on the bulk composition of the ash, a portion was run on a Jarrell-Ash emission spectrograph. A 20 mg sample of the ash was thoroughly mixed with 30 mg of graphite, and this mixture was packed into a carbon electrode. The sample was then burned in a carbon arch, and the visible portion of the emission spectrum was collected on a pair of photographic plates. After being developed, these plates were checked for the presence of each of the naturally-occurring elements in the earth's crust. This check was made by comparing the sample spectrum to a set of USGS standard plates for each individual element which had been prepared following a similar procedure. These plates contained spectra from a number of specially prepared samples which spanned a range of concentrations of the particular element. The attached table lists the elements detected and estimated amounts present in the ash, and compares this data with a similar analysis of ash from the 18 May 1980 eruption of the volcano taken from USGS open file report 80-740. Major element contents were quite similar in both samples, but these were some variations for particular minor elements. This is especially true for some of the metals - Co,Cr,Ni,Pb,Sn, and Mo. Whether or not these high values represent possible metal contaminants from the engine is not known, but an initial effort was made to remove all visible metal fragments from the ash sample prior to analysis. With the exception of these elements, values of the other constituents seem to be consistent with published data.

From the above analysis of the ash sample, the following conclusions seem warranted:

(1) the sample is composed of several common silicate minerals plus some rock fragments, and seems to be representative of typical volcanic ash material.

(2) particle size falls in the range of 0.50-0.05 mm.

(3) most grains appear irregular in shape although they are roughly of equal dimensions.

(4) on the Mohs hardness scale, the minerals present in the ash have values

[redacted]

in the range of 5-6. Although not a linear scale, quartz has a hardness of 7, while corundum has a value of 9 according to this measure of mineral hardness.

(5) grain appearance, a lack of visible evidence for partial melting, the determined melting temperature range of 1200-1400°C of the ash, and the nature of the constituent minerals themselves, suggest that this material had not been subjected to temperatures above 1000-1100°C in the aircraft engine.

(6) the volume proportion of glassy material in the ash is estimated to be less than 5%.

(7) spectrographic evidence indicates a similarity in major and some trace elements between this sample and other published data on ash from the volcano.

(8) discussion with members of the geology faculty indicates that gross changes in ash composition, mineralogy, and physical properties would not be expected during the period 18 - 25 May 1980. A scan of a series of USGS reports on the volcano has revealed no measured changes in the properties of the ash from Mount St. Helens during the period ending in December 1980.

Analytical work performed by James Shigley
Graduate Student, Geology Department, Stanford University
23 July 1981

James Shigley

Analytical work and data interpretation supervised by Professor Gordon Brown
Associate Professor of Mineralogy, Department of Geology, Stanford University
23 July 1981

Gordon E. Brown Jr.

[redacted]

[redacted]

COMPARISON OF SPECTROGRAPHIC ANALYSES - MOUNT ST. HELENS ASH

Semiquantitative analyses of emission spectra of two ash samples
precision of analyses (± 50 percent)

	Ash sample from aircraft engine	Ash sample from USGS open file report 80-740
	percentage of sample, be weight	
Iron	5	3
Magnesium	1.5	1
Calcium	5	3
Titanium	0.15	0.3
Silicon	> 10	> 10
Aluminum	10	7
Sodium	3	2
Potassium	1	1
Phosphorus	N	0.04
	parts per million (ppm) of sample, by weight	
Manganese	1500	700
Silver	15	< 0.2
Arsenic	N	2
Boron	N	10
Barium	300	300
Beryllium	1.5	2
Cadmium	15	0.2
Cobalt	200	20
Chromium	300	7
Copper	100	30
Lanthanum	10	20
Nickel	500	10
Lead	300	10
Scandium	10	15
Strontium	1000	500
Tin	70	< 2
Vanadium	50	70
Yttrium	5	15
Zinc	100	100
Zirconium	150	150
Gallium	15	30
Ytterbium	5	2
Molybdenum	70	< 2

N = not detected

[redacted]

AIRCRAFT ENGINE NUCLEAR DUST INGESTION

AN ANNOTATED BRIEFING

By F. Parry

Presented to

Dr. H. Cooper, USAF/OSAF

June 1981

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AIRCRAFT ENGINE NUCLEAR DUST INGESTION

JUNE 1981

F. PARRY

79

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INTRODUCTION AND BRIEFING OUTLINE

The former briefing and report dated 04 March 1981 identified a possible serious environment problem for aircraft and for cruise missiles that might be incurred by flying through dust clouds encountered after nuclear surface or near-surface bursts. This was based on early reports following the encounter of a Hercules (C-130) aircraft with the second (25 May 1980) Mt. St. Helens volcano eruption. These early reports indicated a serious deposition of glass on the stator vanes in the turbine. This deposition as reported (from 1/8 to 3/8 in. thickness) would be sufficient to block the flow passages of the turbine and result in severe compressor surge. As a result of this, it was decided to examine in more detail what precisely happened in this Mt. St. Helens incident. Engineering reports of the engine strip down and conversations between the pilot and the control tower and personal conversations with the pilot of the aircraft were held. As a result the perspective of this incident was changed. In this briefing we present an overview of the prior results and the new data from the revisit of the Mt. St. Helens incident. Since the C-130 aircraft was first produced in 1952, its engines (P-56 turboprops) are of a design which is not representative of the more modern trends. The modern engine trends are examined. The glassification potential which might arise in a late time nuclear dust environment is examined and a test plan is proposed to resolve the outstanding issues associated with the potentially serious environmental effect. This proposed test plan was suggested by Dr. H. Cooper, Deputy for Strategic and Space Systems.

[redacted]

BRIEFING OUTLINE

- OVERVIEW
  - PRIOR RESULTS/NEW DATA
- MT. ST. HELENS REVISITED
- ENGINE TRENDS
- GLASSIFICATION POTENTIAL
- PROPOSED TEST PLAN

[redacted]

OVERVIEW

As discussed in the introduction, the primary Mt. St. Helens reports were found to be inadequate and the detailed investigation of the C-130 incident of May 1980 showed that the probable failure was initiated by compressor erosion. From the data examined in detail three main inferences could be drawn as shown in the chart. In summary it was concluded that this failure was caused by an excessive concentration of dust of unknown size distribution resulting in a very rapid failure with heavy deposits through the engine. Glassification in the turbine stators of the engine was present and of such magnitude that this glassification by itself could have caused failure. The excessive dust concentration resulted in compressor erosion with attendant irregular combustion such that the combustion flame spread through the turbine with a resultant melting of the first two stator rows and burning of the turbine blades. The glassification problem of nuclear dust cloud environment was in no way refuted and it is concluded that new engines with higher turbine temperatures and cool stator and rotor blades could be even more susceptible to this glassification problem.

OVERVIEW

- PRIOR MT. ST. HELENS REPORTS WERE INADEQUATE
- DETAILED INVESTIGATION OF C-130 INCIDENT SHOWED PROBABLE FAILURE INITIATED BY COMPRESSOR EROSION
- INFERENCES:

  1. DUST ENVIRONMENT MUCH HIGHER THAN ENGINE TEST SPECIFICATIONS
     - CERTAINLY IN CONCENTRATION, MAYBE IN SIZE DISTRIBUTION
     - RAPID (FEW MINUTES) FAILURE RATE, AND HEAVY DEPOSITS
  2. DUST ENVIRONMENT EXTREMELY INHOMOGENOUS
     - ONE OUTBOARD AND ONE INBOARD ENGINE FAILED COMPLETELY
     - OF OTHER TWO ENGINES ONE WAS REPAIRABLE
  3. GLASSIFICATION PROBLEM OF NUCLEAR DUST CLOUD ENVIRONMENT NOT REFUTED
     - GLASSY DEPOSITS WERE FOUND IN TURBINE SECTION

- NEW ENGINES WITH HIGHER TURBINE TEMPERATURES AND COOLED STATOR AND ROTOR BLADES COULD BE MORE SUSCEPTIBLE TO GLASSIFICATION PROBLEM

THE MT. ST. HELENS INCIDENT

This chart gives a brief history of the nomenclature and production of the Hercules aircraft with a top level summary of the May 25th incident.

MT. ST. HELENS INCIDENT

- AIRCRAFT
  - LOCKHEED MODEL 382 "HERCULES"
  - MILITARY DESIGNATION C-130
  - COMMERCIAL DESIGNATION L-100 OR L-382
  - 4 ALLISON T-56 TURBOPROPS
  - FIRST PRODUCTION CONTRACT 1952 (C-130A - 461 DELIVERED)
  - FOLLOW-ON 1962 (C-130E, MODEL 382-44 - 503 DELIVERED BY 1975)

- 25 MAY 1980 TRANSAMERICA FLIGHT 222/146 FROM McCHORD AIR FORCE BASE TO TRAVIS AIR FORCE BASE HAD A VOLCANIC ASH ENCOUNTER
  - DEPART McCHORD 1137Z (≈1 1/2 HOURS AFTER ERUPTION)
  - #4 ENGINE EXPERIENCED STALL, SURGE, BACKFIRE (ABOUT 16,000 FT)
  - ENGINE SHUTDOWN 1153Z
  - #2 ENGINE SIMILAR EXPERIENCE, SHUTDOWN 1155Z
  - RETURNED ON 2 ENGINES TO McCHORD AIR FORCE BASE 1214Z

C-130 REPORTS

A summary is given of the highlights of the conversation between the air traffic control and captain of the aircraft. Times of these highlight comments are given from the start of the tape (the tapes started a few minutes after takeoff from McChord Air Force Base as the aircraft flies through 35,000 ft). An addendum to the conversation is given of an interview with the captain immediately subsequent to the flight.

C-130 REPORTS

• AIR TRAFFIC CONTROL TAPE HIGHLIGHTS SUMMARY

	COMMENT	TIME AFTER TAPE START (MIN/SEC)
1.	AT 11,500' REPORTED BETWEEN LAYERS OF MURKY GRAY CLOUDS (REGULAR WEATHER CLOUDS).	5.30
2.	PASSED THROUGH LAYER AT 12,700' AND OUT AGAIN AT 13,500' WITH BIG VOLCANIC CLOUD AHEAD.	7.32
3.	BEGIN TO NOTICE (VOLCANIC) SMELL AND TURNING WEST FOR AVOIDANCE.	8.40
4.	STILL NOTICE SMELL AT 15,000', AND DARKNESS - NO RADAR ON.	9.55
5.	STILL IN CLOUD ALTHOUGH MOVING WEST.	11.16
6.	TURNING NORTH - #4 ENGINE LOST, RETURNING TO McCHORD.	11.44
7.	#2 ENGINE LOST.	12.28

• SUBSEQUENT REPORT

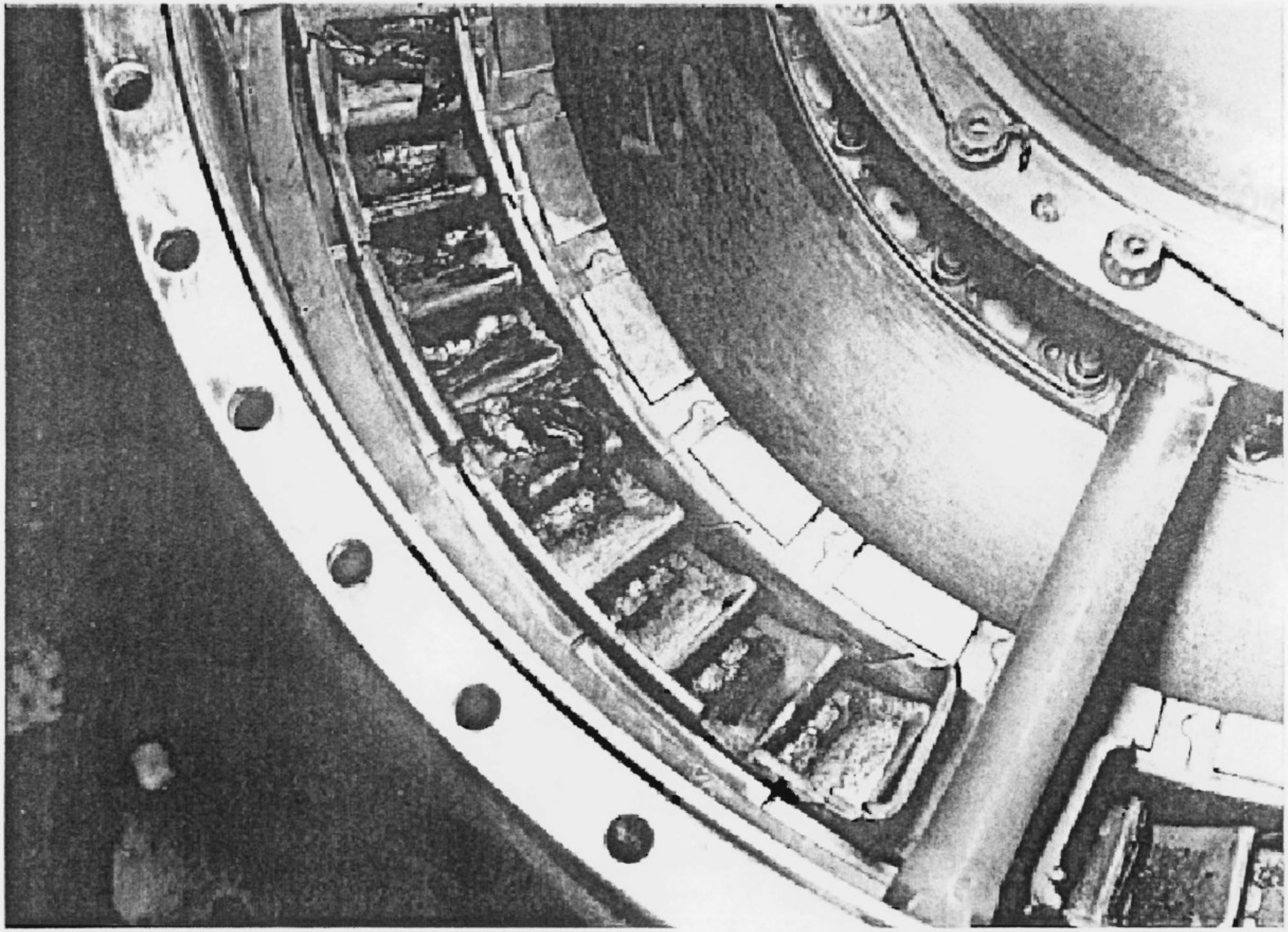
AFTER SMELL FIRST NOTICED:

"Shortly thereafter, approximately 2 or 3 minutes, #4 engine began to stall, surge, and generate what the Captain described as a backfire. The engine operation became uncontrollable and it was necessary to shut the engine down (feather). This occurred at 1153Z. At approximately 1155Z, #2 engine suffered the same type of failure, and Captain Tripp was forced to shut down that engine."

PHOTOGRAPHS OF C-130 ENGINE FAILURE

Charts 5 through 10 show photographs of various aspects of the failure. These photographs were taken from No. 4 engine which was the first one to fail. Although these photographs do show accumulations of dust and debris and damage to blades, they are not as dramatic, in general, as a visual inspection of the actual parts. An actual stator section (a segment of six second stage stator blades as shown in Chart 7) was shown at the various times at which this briefing was given. Chart 9 shows an enlarged photograph of a deposit from a third stage stator blade. This is a deposit referred to in prior literature as 1/8 to 3/8 in. thick. Such deposits which occurred throughout the third stator row would be sufficient in themselves to choke the turbine and result in overall engine surge. Chart 10 shows a temperature probe which is partially blocked with the dust and debris accumulations. An analysis is being made of the chemical composition and physical characteristics of debris from the engine. Results of this analysis have not yet been obtained.

FIRST STAGE STATORS



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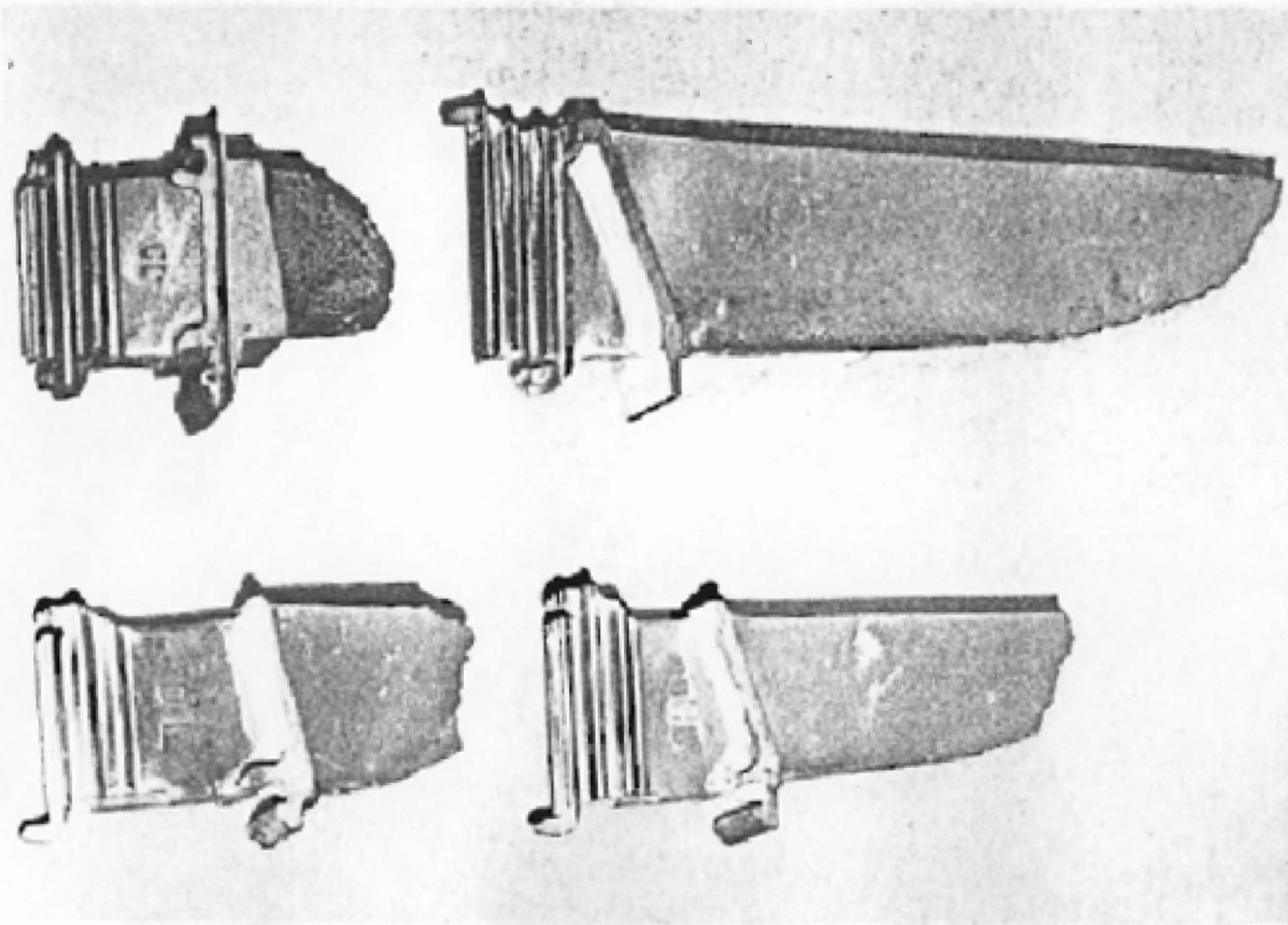
FIRST, SECOND, THIRD AND FOURTH STAGE TURBINE BLADES



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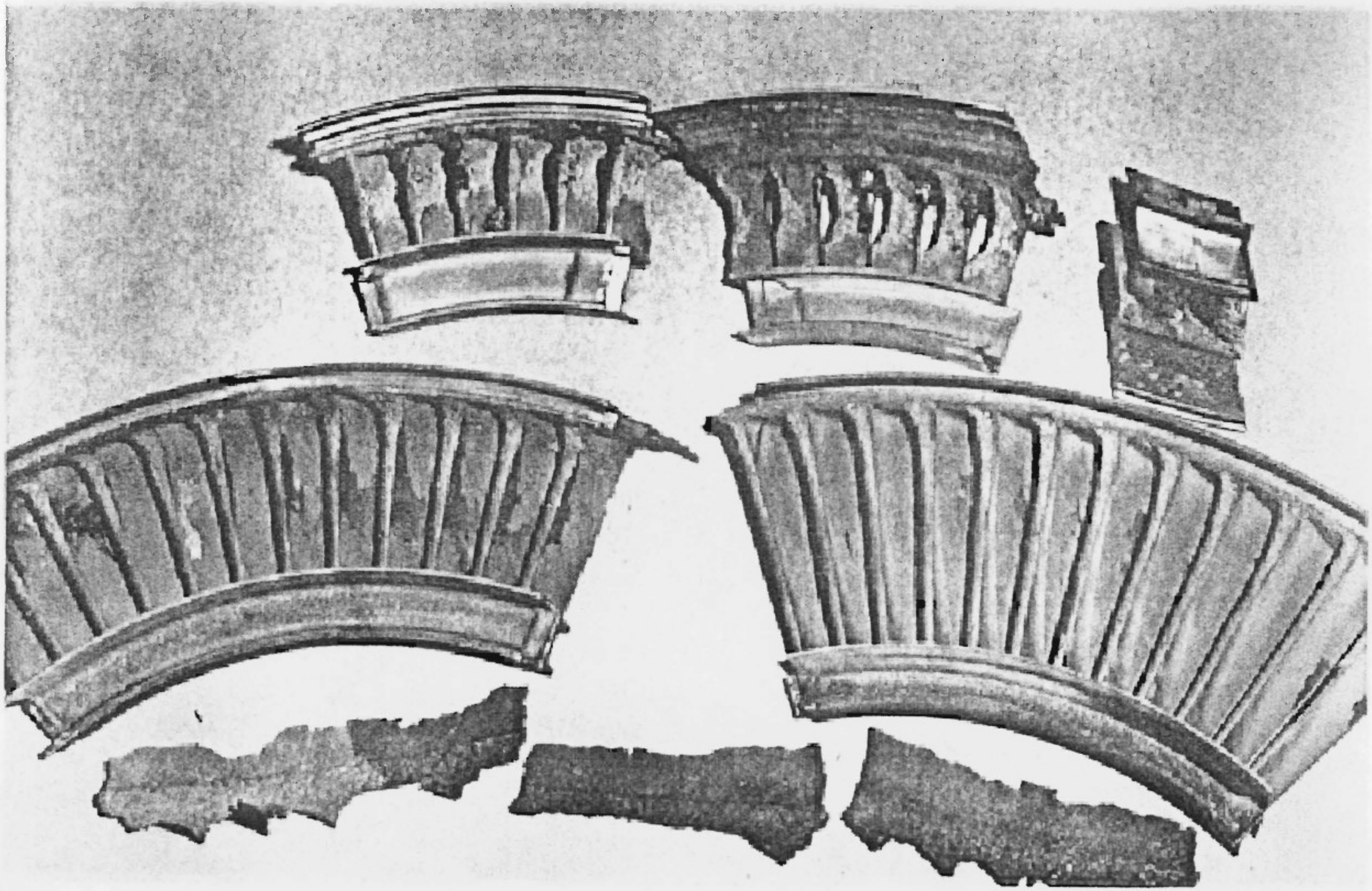
SECOND, THIRD AND FOURTH STAGE STATORS



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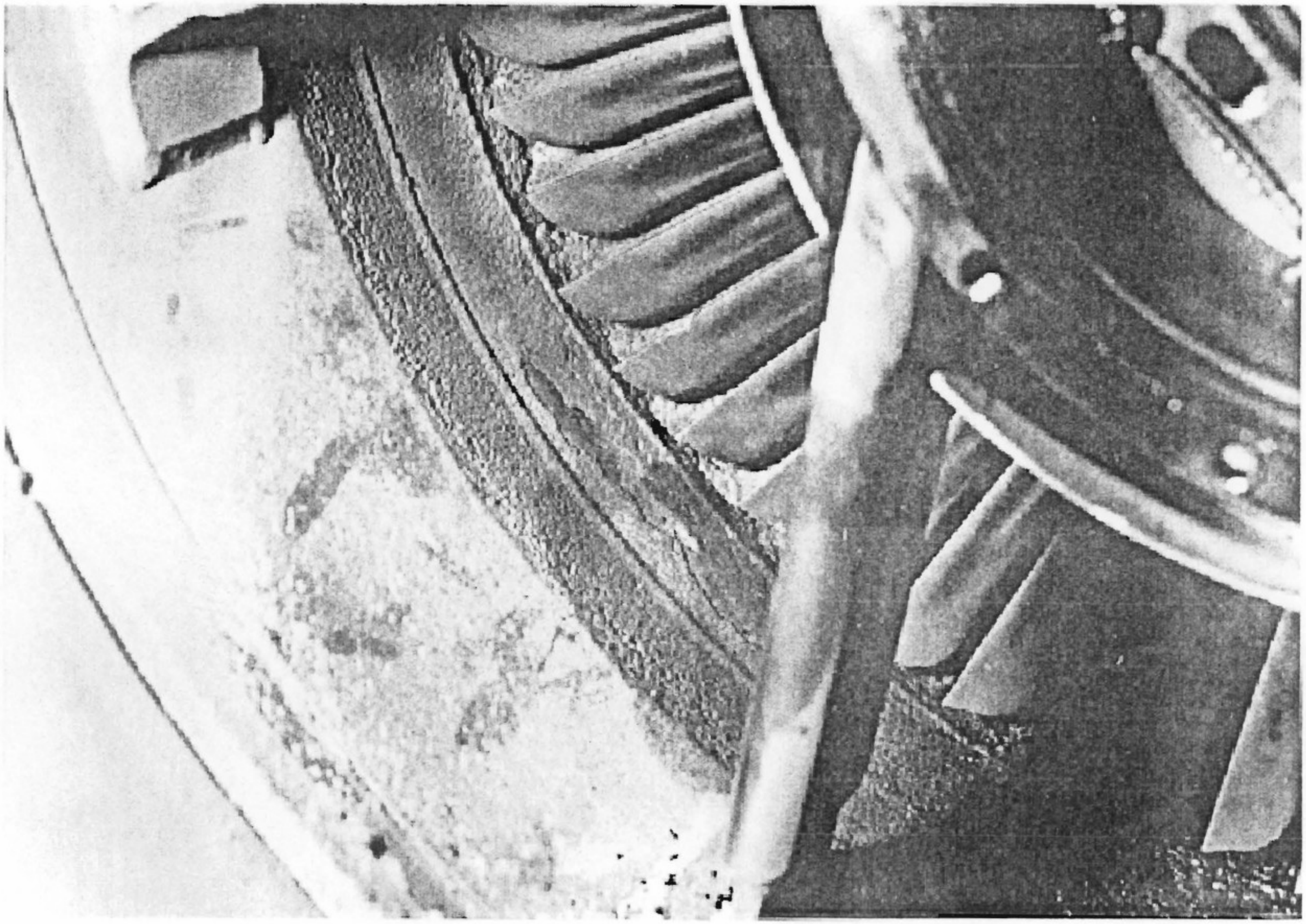
TURBINE BLADES/HOUSING



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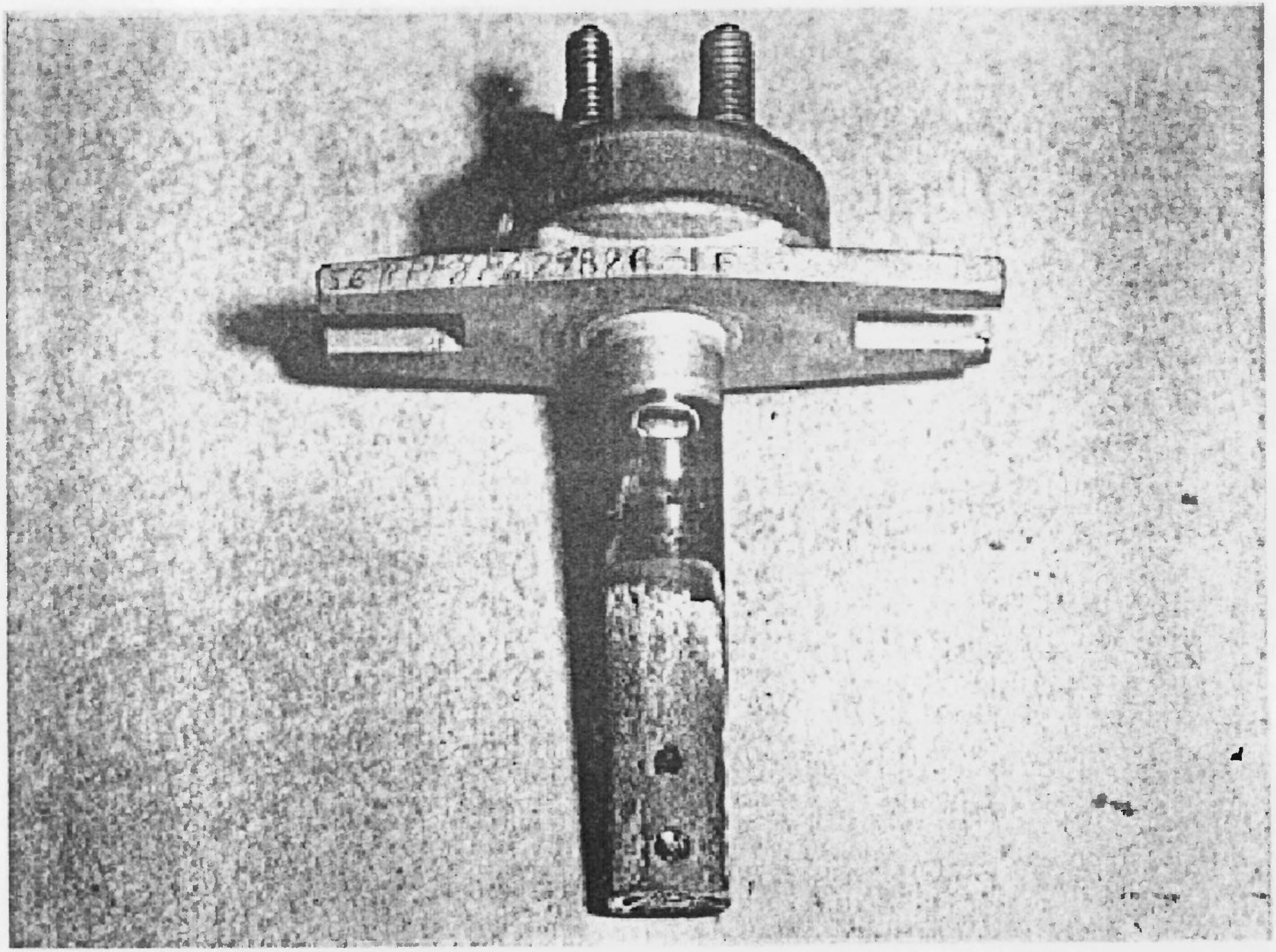
TEMPERATURE PROBE



C-130 (AIRCRAFT #24ST) ENGINE DAMAGE

This chart summarizes the engine damage and repairs that were necessary. No. 4 was the first engine shutdown followed two minutes later by engine No. 2. No. 4 was the starboard outer engine and No. 2 the port inner engine. The aircraft returned to McChord on engines No. 1 and No. 3. Post-flight examination revealed that engines No. 4 and No. 2 which were shutdown required complete replacing as did engine No. 1. In these three engines, the compressor suffered heavy erosion and the turbines suffered over-temperature damage. In many places the turbine blades and stator vanes were badly burned or melted. Engine No. 3 was not quite so badly damaged. The compressor suffered light erosion and the turbines suffered some over-temperature damage. This engine was repaired by replacing the turbine and fuel control unit.

[redacted]

C-130 (A/C #24ST) ENGINE DAMAGE

ENGINE #	1 P.O.	2 P.I.	3 S.I.	4 S.O.
COMPRESSOR	HEAVY EROSION	HEAVY EROSION	LIGHT EROSION	HEAVY EROSION
TURBINE	OVERTEMP DAMAGE	BLADES/VANES BURNED	OVERTEMP DAMAGE	BLADES/VANES BURNED
REPAIR	ENGINE REPLACED	ENGINE REPLACED	TURBINE AND FCU REPLACED	ENGINE REPLACED

NOTE: PHOTOS WERE FROM ENGINE #4

DURING ASH ENCOUNTER #4 ENGINE WAS SHUTDOWN FIRST FOLLOWED 2 MINUTES LATER BY ENGINE #2

[redacted]

MT. ST. HELENS ASH

An analysis of Mt. St. Helens dust taken some time after the first explosion but prior to the May 25th incident was made by the Boeing Company and this chart summarizes those results. The particle size distribution was obtained from ground samples some hundred miles from Mt. St. Helens. It should be noted, that in general the particle size does not exceed 50 microns.

[redacted]

[redacted]

[redacted] [redacted]

MT. ST. HELENS ASH

BOEING REPORT MAY 1980

- ABRASIVENESS - HIGH, APPROXIMATELY 6 ON MOH SCALE (QUARTZ = 7, DIAMOND = 10)
- TEXTURE
  - RESEMBLES TALC
- ACIDITY
  - GROUND SAMPLES NEUTRAL (PH 5.2 - 6.8)
  - SAMPLES FROM 55,000 TO 60,000 FT HIGHLY ACIDIC (PH2)
- CONSTITUENTS

  MAJOR: SI, AL, K, CA, FE, CU, O

  MINOR: TI, S, Cl

  TRACE: FL
- PARTICLE SIZE DISTRIBUTION (GROUND SAMPLE 100 MILES FROM MT. ST. HELENS)

MICRONS	PERCENT
<5	70
5-15	28
15-25	1.4
25-50	0.3
>50	TRACE

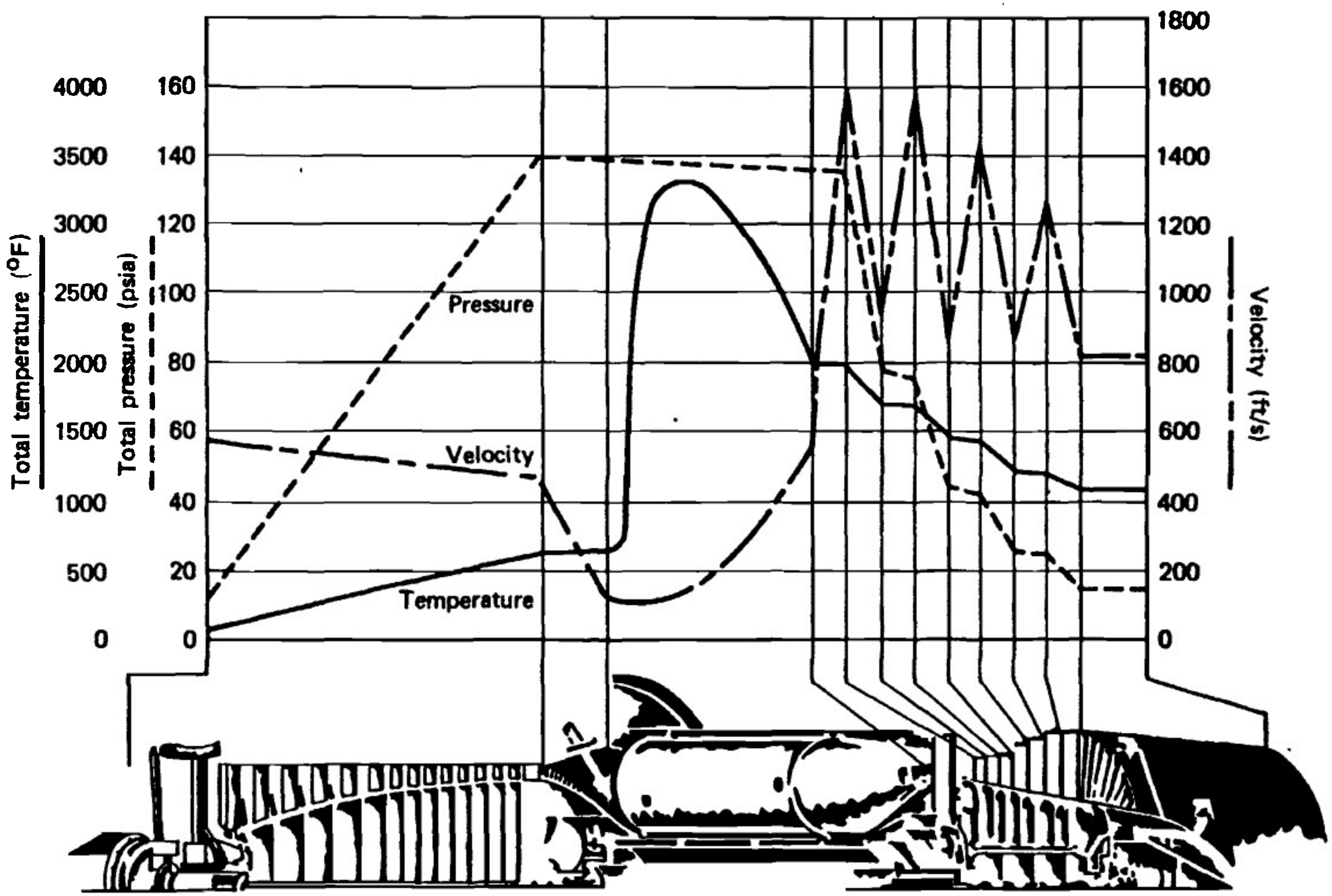
PRESSURE, TEMPERATURE AND VELOCITY DIAGRAM

T-56 ENGINE

This chart shows the velocity, total pressure, and total temperature through the C-130 engine. The chart (supplied by the Industrial Division of Allison), as was discussed in prior briefings, shows that in the primary zone of the combustion chamber close to stoichiometric temperatures with a maximum of 3800°F occur. Mixing then takes place giving a turbine inlet temperature of 2000°F. The values are typical of a 1952 vintage engine.

PRESSURE, TEMPERATURE AND VELOCITY DIAGRAM

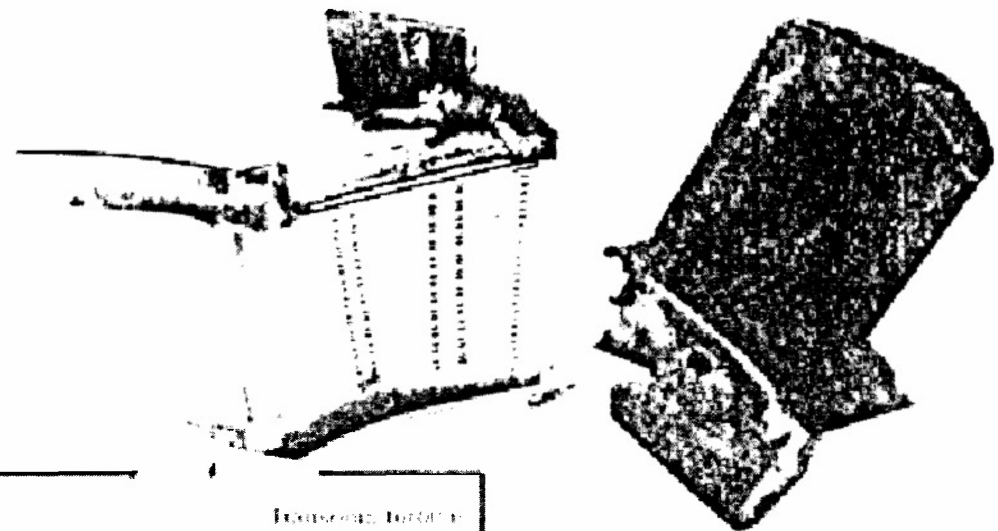
T-56 ENGINE

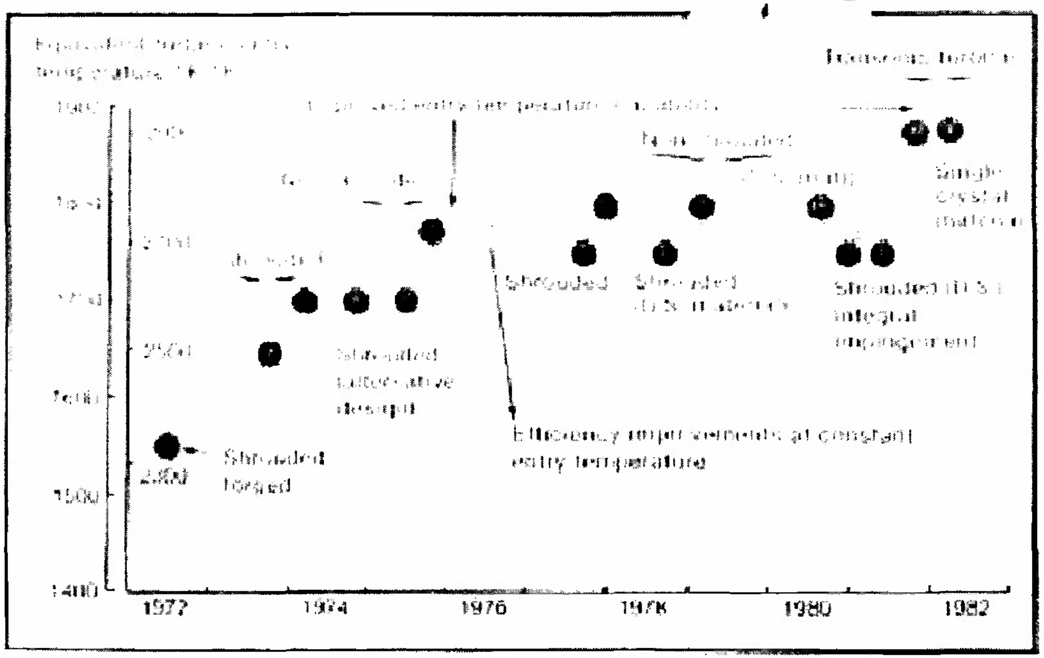


ENGINE GROWTH TRENDS

This chart shows aircraft engine growth trends. Test points and scheduled test points are shown. By 1972 engines with 2300°F turbine inlet temperature were being run. This grew to 2700°F by 1976 and currently temperatures of 2900°F are being considered. In all these cases, intensive cooling of both stators and turbine blades is necessary. The complexity of the cooling systems is shown by the photograph of a typical stator and turbine blade in the top right hand of the chart.

ENGINE GROWTH TRENDS





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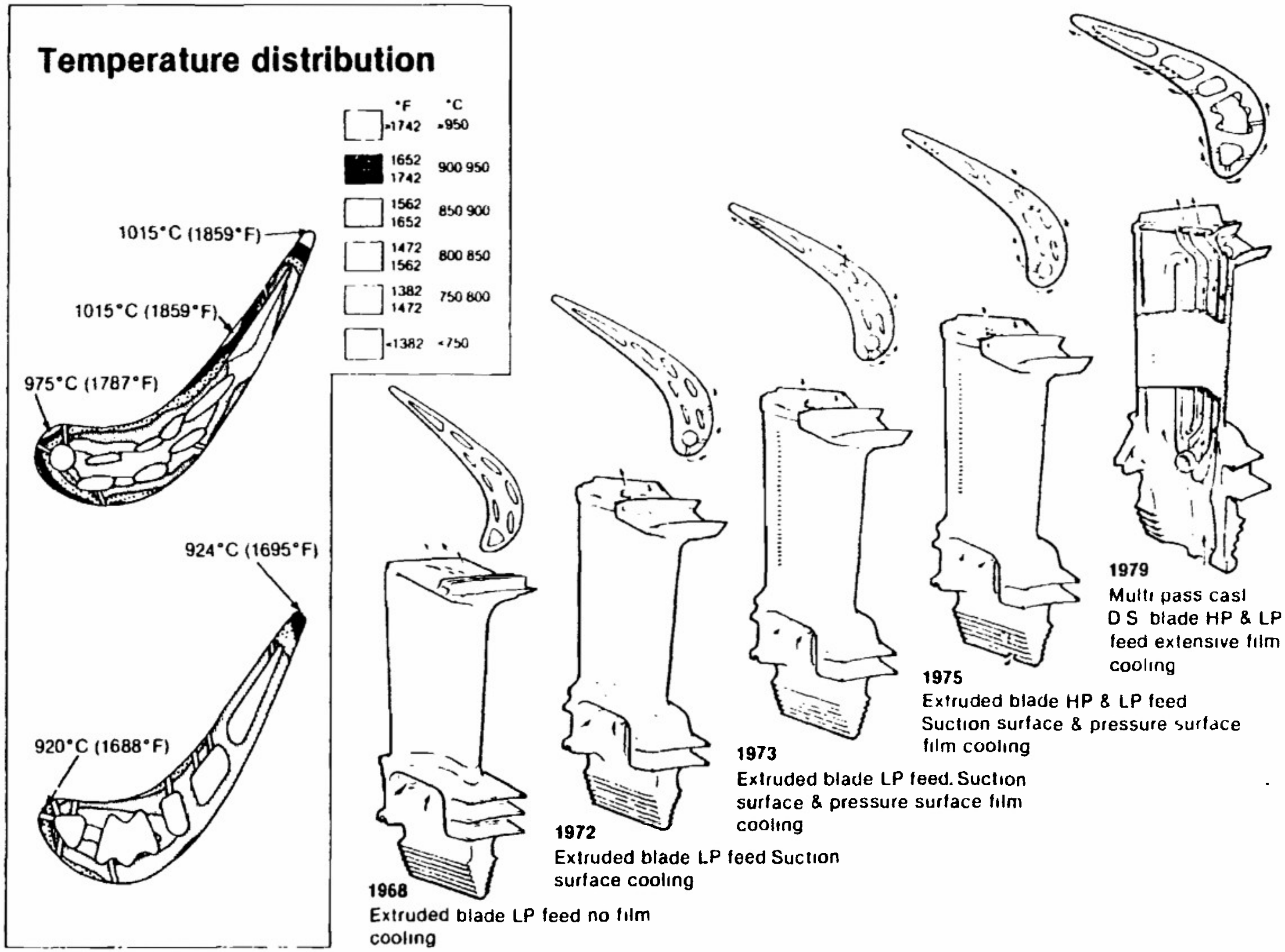
TURBINE BLADE COOLING TECHNOLOGY

This chart shows the growth in cooling technology for turbine blades. It should be noted that the maximum metal temperature which can be tolerated is around 1860°F with the best modern materials. With turbine inlet temperatures approaching 2900°F this means that extensive cooling is required. The turbine inlet temperatures approaching 2900°F this means that extensive cooling is required. The turbine blades thus grew from simple through passages, as shown in the 1968 extruded blade to complex passages with shrouding of the tips and film-cooling of the late 1970 blades.

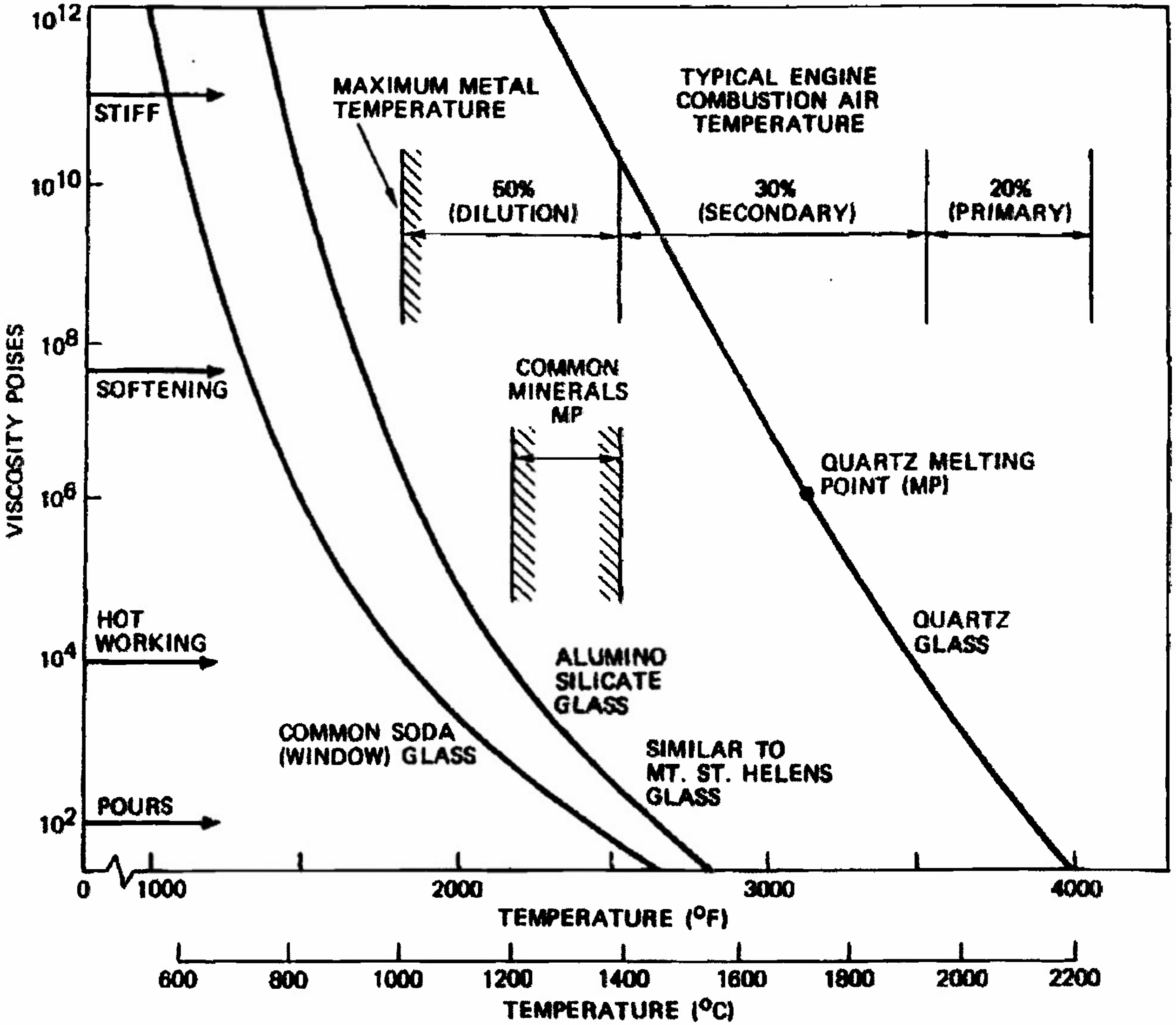
TYPICAL COOLED TURBINE BLADES



GLASSIFICATION POTENTIAL

In order to appreciate the glassification potential and its application to the engine growth trends of the prior two charts, this chart is updated from the prior briefing and shows that there is a broad temperature range over which common materials could be readily glassified into reasonably low viscosity liquid. Such glasses would adhere to metallic surfaces and form sticky films in the boundary layers on the cooled turbine stator and rotor blades. They would probably be manifested as deposits on the stator blades but not on the rotor blades since centrifugal force would be sufficient to keep the rotor blades clean. For example, an alumino-silicate glass similar to Mt. St. Helens would be a semi-liquid at about 2400°F and would be quite sticky at about 1900°F (the maximum allowed cooled blade metal temperature). This obviously could result in permanent deposition with buildup in low gas velocity regions. With the many complex cooling holes and passages of the modern blades this could result in blockage of the cooling passages with attendant overheating and failure of the subject blades. This chart also demonstrates the more difficult requirement for quartz to result in glassification as discussed in the previous briefing. Thus, the relevance of the engine specification (which requires crushed quartz for erosion tests) to glassification is still questionable, even for the more modern engines.

GLASSIFICATION POTENTIAL



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Pages 106 through 111 are deleted.

AIRCRAFT ENGINE DUST INGESTION PROBLEM

FIRST, SECOND AND OVERALL PROGRAM PLAN

At the request of Dr. Cooper, a full test program was structured. This test program was discussed with Dr. Mike Dunn of Calspan and is divided into three phases. Phase I is shown in chart 20 and Phase II in chart 21. Phase III is not addressed here but this would be a full engine test program. In Phase I, it is suggested that the problem be defined in greater depth clarifying some of the unknowns by simple lab tests. Further work is currently being done to structure the simple lab tests in detail. Some of tasks outlined in this first year program plan have already been attacked. Thus, for example, further studies of the Mt. St. Helens environment have been carried out, preliminary work has been done on the chemistry of the Mt. St. Helens particles and data has been gathered on the expected increase in desired top temperatures of modern turbine engines. Phase II would essentially extend the experimental testing to actual engine combustion chambers. The exact scope of this phase would depend on the outcome of Phase I. The first two phases would normally be of one year extent as shown in the upper schedule of chart 22. These two phases could be carried out for a combined cost of about $410,000 as indicated and would proceed into Phase III for full scale engine tests (if required in year three). It would be possible to accelerate this program and go into full scale engine tests in the second year as shown in the lower schedule of chart 22.

AIRCRAFT ENGINE DUST INGESTION PROBLEM
FIRST YEAR PROGRAM PLAN

- OBJECTIVES (PHASE I):
  1. DEFINE THE PROBLEM IN GREATER DEPTH
  2. CLARIFY SOME UNKNOWNS BY SIMPLE LAB TESTS
  3. PREPARE TEST PLANS FOR PHASE II

- FUNDING:
  $160K

- TASKS:
  1. EXAMINE RELEVANCY OF MT. ST. HELENS TO NUCLEAR ENVIRONMENT
     - DETAIL ANALYSIS OF "WHY DID L100 (T56's) HAVE A PROBLEM?"
     - OVERLAY MAP OF OTHER ENGINE OPERATIONS IN MT. ST. HELENS ENVIRONMENT AND "WHY NO PROBLEM?"
  2. ANALYZE ENGINE OPERATING CONDITIONS AND THEIR RELEVANCY TO PROBLEM
     - GAS TEMPERATURES, RESIDENT TIMES, METAL TEMPERATURES, COAL BURNING PLANTS
     - PARTICLE HEATING AND DEPOSITION THEORY
     - GLASSIFICATION EFFECT ON SURGE MARGIN AND BLOCKAGE OF COOLING PORTS
     - EFFECT OF INCREASING DESIGN TOP TEMPERATURES
  3. COMPARE MT. ST. HELENS PARTICLES WITH NUCLEAR CLOUD PARTICLES
     - SIZE, SHAPE, DISTRIBUTION, CHEMISTRY
     - FALLOUT PROFILES
  4. CHARACTERISTICS OF NUCLEAR CLOUDS RELEVANT TO GLASSIFICATION AND EROSION
     - CATEGORIZE MX AND MM SOILS
     - INITIATE LAB TESTS (E.G., UNIV. OF NEW MEXICO)
  5. DEVELOP CLOUD PATTERNS/SCENARIOS FOR ALCC (AND OTHER AIRCRAFT AS REQUIRED)
  6. STUDY OF POSSIBLE FIXES
     - BYPASS BLEED DOORS? OVER TEMPERATURE CYCLE? OTHER?
  7. FORMULATE COMBUSTION RIG TEST PLANS AND SELECT SUITABLE SUBCONTRACTORS FOR PHASE II

AIRCRAFT ENGINE DUST INGESTION PROBLEM
SECOND YEAR PROGRAM PLAN

- OBJECTIVES (PHASE II)
  1. CONFIRM EXPERIMENTALLY THE CONDITIONS FOR GLASSIFICATION BY USING A COMBUSTION TEST RIG
  2. CONTINUE AND EXTEND SUPPORTING ANALYSES
  3. PREPARE TEST PLANS FOR PHASE III (IF REQUIRED)

- FUNDING:

  $250K

- TASKS:
  1. DEFINE FLOW DIAGNOSTIC MEASUREMENTS/INSTRUMENTATION
  2. CARRY OUT COMBUSTION EXPERIMENTS WITH SELECTED DUST SAMPLES AND CONCENTRATIONS TO DETERMINE:
     - CONDITIONS FOR DEPOSITION
     - RELATIONSHIP BETWEEN DEPOSITION PARAMETERS (TEMPERATURE, FLOW FIELD, PARTICLE SIZE AND COMPOSITION, ETC.)
  3. INVESTIGATE EFFECTS ON IGNITERS, TEMPERATURE PROBES, COOLING PORTS
     - IF PROBLEM - HOW CAN IT BE REDUCED?
  4. DETERMINE EFFECT OF FILM COOLING
  5. INVESTIGATE METHODS OF REMOVAL (E.G., TEMPERATURE CYCLING)
  6. REVIEW EFFECT OF RISING DESIGN TOP TEMPERATURES
  7. CONTINUE SUPPORTING ANALYSES
  8. (IF NECESSARY) PREPARE FULL SCALE ENGINE TEST PLANS (PHASE III)

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AIRCRAFT ENGINE DUST INGESTION PROBLEM
OVERALL PROGRAM PLAN

A. STANDARD PROGRAM (EASY)

ITEM	YEAR 1	YEAR 2	YEAR 3 +	$K
PHASE I				
1. PROBLEM DEFINITION				120
2. SIMPLE LAB TESTS				40
3. PHASE II TEST PLAN				-
PHASE II				
1. COMBUSTION RIG TESTS				200
2. SUPPORTING ANALYSES				50
3. PHASE III TEST PLAN				
PHASE III				
FULL SCALE ENGINE TESTS				$2M+

B. ACCELERATED PROGRAM (DIFFICULT)

ITEM	YEAR 1	YEAR 2	YEAR 3 +	$K
PHASE I				
1. PROBLEM DEFINITION/LAB TESTS				175
2. PHASE II TEST PLAN				
PHASE II				
1. COMBUSTION RIG TESTS				
2. ANALYSES				300
3. PHASE III TEST PLAN				
PHASE III				
FULL SCALE ENGINE TEST				$2M+

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Appendix D

POSSIBLE LABORATORY TESTS TO DETERMINE THE MELTING CHARACTERISTICS OF ROCK AND SOIL DUST THAT MAY POSE A THREAT TO AIRCRAFT ENGINES

By

G. Rawson

[redacted]

INTRODUCTION

The purpose of these tests is to assist in determining if the Defense Department needs to thoroughly investigate vulnerability of aircraft engines to lofted dust. The problem was brought into focus as a result of the May 25 eruption of Mt. St. Helens in which an aircraft suffered severe engine damage due to the accumulation of melted dust (glass) on the turbine blades. This experience serves only as a qualitative indication of a damage mode which, potentially, could be more serious than those engine damage modes considered previously (abrasion, oil contamination, etc.). However, Mt. St. Helens dust is included in the program so that the results can be related to the above-mentioned experience.

The dust from Mt. St. Helens is largely volcanic glass (a supercooled liquid with traces of minerals or crystalline matter). It is expected to remelt to sufficient fluidity to flow at about 800° to 1000°C. This is somewhat lower than melting conditions for most rock and soil particles. Very fine dust particles can, however, experience rapid heat exchange. The temperatures within parts of jet engines are sufficient to melt most minerals if enough particle residence time is available for the exchange of sufficient heat.

Small quantities of Mt. St. Helens dust, collected 200 km downwind of the eruption, can be obtained from one of the researchers studying the eruption. These samples would serve as a particle size and shape reference, as well as a chemical and mineralogical reference for the tests. Other Mt. St. Helens material would be obtained and sorted to provide similar samples should more material be needed for the tests.

PROPOSED EXPERIMENTS

The dust melting experiments described herein are designed to bracket the dominant mineralogical and chemical assemblages common to possible nuclear attack targets by an adversary (e.g., strategic facilities in remote valleys wihin the Western U.S.) The tests are intended to be low cost, timely and preliminary in nature, yet expected to provide sufficient data to allow efficient assessment of the dust threat.

Expected variations in melting characteristics for dust from different soils and rocks will depend largely upon (1) details of the mineral/chemical assemblage, (2) particle size and shape, (3) amount of glass and water present, and (4) the pressures applied with the heat upon the dust particles. Appendix A provides a brief review of some rock and soil geochemistry and past melting experiments, which serve to inform the reader and guide selection of the appropriate samples for these experiments.

A fundamental particle size assumption proposed for these tests is that the smaller one-third of the particle size distribution for the samples obtained about 200 km east of Mt. St. Helens represents dust that lingers and poses a threat to aircraft. This smaller one-third of the total sample would be further split into the relatively coarser and finer fractions (designated MSHC and MSHF). These two reference samples would then be tested and characterized as follows.

1. Particle size and shape analysis using a scanning electron microscope (SEM).
2. Major and minor element chemical analysis using emission spectroscopy and X-ray techniques.
3. Determine the ratio of glass to crystalline fractions using X-ray and optical methods.
4. Determine water content by weight loss upon heating from room temperature to the partial melting threshold.
5. Conduct repeated furnace runs for comparison documentation of temperature, melt fraction, apparent fluidity and other observations from initial partial melting conditions to total fusion.

At selected temperature, based upon experience and the estimates shown in Table 4 of Appendix A, cone-shaped samples would be placed in the furnace and removed one at a time at regular intervals. These runs are to document fluidity. Glass/crystalline

ratios would be determined and compared with Step 3 above. These runs and the above-listed five steps would be repeated on all of the test samples (Table 4, Appendix A). Modifications of the runs would be made as experience is gained to make the tests efficient and yet provide definitive results.

The rock and soil types for these experiments and discussed further in Appendix A are:

(1) *MSH - Mt. St. Helens volcanic glass dust
(2) *WSG - White Sands gypsum dust
(3) MC - Montmorillonite clay dust
(4) *YVLS - Yucca Valley Lake sediments dust
(5) GMGS - Gold Meadows granitic soil dust
(6) *MBS - Monterey (quartz) beach sand dust
(7) RMD - Ranier Mesa dolomite (carbonate) dust.

Each type would be split into coarse (C) and fine (F) designation. Very complete documentation of the four (asterisk-labeled) samples should be made, as these are considered most pertinent to the expected field conditions and experience that can be directly linked to aircraft engine damage. Possibly two different types of clay minerals having two different contents of water of crystallization should be studied to help estimate the importance of water content on changing the melting conditions of silicate minerals. The carbonate test may examine limestone ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] separately, and only examine sintering or particle adhesion in the presence of melt since CaO and MgO are so refractory.

Following is a listing of the estimated quantities of the various types of experiments and analyses.

1. Fourteen particle separation to MSHC, MSHF, etc., and SEM on each.
2. Fourteen major and minor element analyses.

3. Ten heating and weight loss (percent water) tests.
4. Fourteen determinations of initiation of partial melting.
5. Fifty glass/crystalline ratio determinations and documentation of apparent fluidity on samples MSH, WSG, YVLS and MBS.
6. Twenty glass/crystalline ratio determination and documentation of apparent fluidity on samples MC-, GMGS and RMD.
7. Approximately 150 separate furnace runs of one to five samples at a time, at preselected temperatures.

Samples would be obtained in quantities of about 0.5 ft^3 each and the unused portions retained for possible future tests, such as actual jet engine damage studies. Locations where the samples are obtained should be clearly documented for future needs.

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Annex A

A Brief Review of Rock and Soil Geochemistry and Melting Characteristics

Since specific sites where dust might be lofted by nuclear attack are not part of this proposed investigation, the bracketing of chemical/mineralogical variability requires an overview and generic approach. Table 1 is the approximate mean composition of the outer earths crust. This approximates the basement rock generally masked by a thin veneer of sediments and soils. This composition can be viewed as the parent to sediments and soils that form by its erosion, chemical alterations and various forms of transport and redeposition.

Table 2 illustrates schematically those dominate categories of chemical partitioning that are associated with forming sediments and soils from the various parent materials. Since most regions derive material from a variety of rock types, actual compositions can be quite different. In general, however, SiO_2 tends to be enriched where redeposition is on or near land and carbonates and evaporates enriched where deposition is distant from land. With repeated crustal cycling, carbonates are commonly exposed within land masses as well as the less soluable evaporates such as gypsum. Thus, soils and sediments typically consist of sand, silt, clay, hydrated iron, carbonates and sulfates (hydrated $CaSO_4$).

The Playa Lake sediments of Yucca Valley at the Nevada Test Site (NTS) can be expected to be rather typical of the processes of chemical partitioning shown in Table 2. The surrounding region is quite varied in rock type with volcanic rocks, granitic rocks, carbonates, metamorphosed clays, etc. The principle deficiency is the common enrichment of SiO_2 from

[redacted]

sandstones. Sandstones are much more common in the Colorado Plateau region than in the Basin and Range province which includes NTS.

In addition to the volcanic dust from Mt. St. Helens, powdered quartz is important to represent the extreme of silica enrichment (Table 2A). Clay would also be an important sediment/soil fraction (Table 2B). NTS Yucca Playa would represent an intermediate case containing carbonates and evaporates as well as clays, glass, silica, and numerous other admixed minerals. Another intermediate class would be decomposed granite or soil derived from granitic rock. The carbonates can be represented by powdered dolomite and evaporates by gypsum. Gypsum commonly forms in desert playas and is the mineral forming White Sands, New Mexico.

An estimate of an average or "typical" chemical composition for near surface sediments and soils within valleys of the Western U.S. is given by Table 3. It is assumed the valley fill is formed from altered and transported shales, carbonates, sandstones, and basement rock. This produces fragments of those rocks plus adsorbed and chemically bound water, clays, and evaporates. Clay is chosen to also represent the composition of slates and shales. Granodiorite is chosen to represent the composition of basement rock. The estimated compositions are shown with water not included and it is introduced in the "other" column along with evaporates. The proportions of the mixtures are shown that together have been combined to estimate the typical Western U.S. Valley fill composition.

The purpose of Table 3 is to illustrate common rock chemistry and their weathered by-products and to guide selection of appropriate samples for the dust melting experiments. Table 4 lists the recommended sample types and where they will be obtained. A listing of estimated temperatures to

accomplish substantial partial melting of these materials is also shown. A review of rock and mineral melting or fusion data was made to guide those estimates. Included as sources of the supporting data are references 3 through 9. The values represent melting conditions at low pressures (a few bars). Increased pressure tends to increase the melting temperatures. Increase water contents tend to lower the melting temperatures. Most of the data are representing equilibrium conditions. Significant departures are expected for the complex mixtures of materials and nonequilibrium heating conditions.

TABLE 1

APPROXIMATE MEAN COMPOSITION OF BASEMENT (NONSEDIMENTARY OR SUPERFICIAL) ROCKS[1, 2]

Elements		Rock Forming Oxides	
O	46.60%	SiO_2	59.12%
Si	27.70%	Al_2O_3	15.82%
Al	8.13%	Fe_2O_3 + FeO	6.99%
Fe	5.00%	M_gO	3.30%
Ca	3.63%	CaO	3.07%
Na	2.83%	Na_2O	2.05%
Mg	2.09%	K_2O	3.93%
K	2.59%	H_2O	3.02%
Other	1.43%	Other	2.70%
	100.00%		100.00%

TABLE 2

CHEMICAL PARTITIONING RESULTING FROM WEATHERING AND OTHER ALTERATIONS OF BASEMENT ROCK TO FORM SEDIMENTS AND SOILS

(MODIFIED AFTER REFERENCE #2 PG. 151)

2A. SILICA SiO_2	2B. ALUMINOSILICATES $K[(SiO_2)_x\ (Al_2O_3)_y]_z$	IRON OXIDES $Fe_2O_3 + FeO$	Ca, Na, K, Mg OXIDES
↓	↓	↓	↓
RESISTENT SiO_2 SAND & SILT	HYDROLYZED TO CLAY	HYDRATED TO $Fe(OH)_3$	SOLUTION & REDEPOSITION AS

SOLUTION & REDEPOSITION AS:

- CARBONATES $CaCO_3$ $CaMgCO_3$
- EVAPORATES $NaCl$ $CaSO_4$, ETC.

[redacted]

TABLE 3

ESTIMATED CHEMICAL COMPOSITION OF NEAR SURFACE SEDIMENTS AND SOILS IN VALLEYS OF THE WESTERN UNITED STATES

COMPOSITION	ASSUMED PERCENTAGES OF HOST ROCK FOR VALLEY FILL COMPOSITION						TYPICAL WESTERN U.S. VALLEY FILL
	CLAY 37%	LIMESTONE 8%	DOLOMITE 7%	GRANODIORITE 25%	SANDSTONE 10%	OTHER 13%	
SiO_2	64.0	1.5	8.0	65.5	93.0	-	50.0
Al_2O_3	20.0	0.5	1.5	16.5	2.0	-	11.9
$Fe_2O_3 + FeO$	5.5	0.5	2.5	4.0	1.0	-	3.4
MgO	2.5	0.5	-	2.5	0.5	-	1.6
CaO	1.0	-	-	5.0	0.5	-	1.7
Na_2O	1.5	0.4	0.4	4.0	0.5	-	1.7
K_2O	4.0	0.2	1.2	2.0	0.5	-	2.1
$CaCO_3$	-	96.0	-	-	0.5	-	7.7
$CaMg(CO_3)_2$	-	-	85.5	-	0.5	-	6.0
$CaSO_4$	-	-	-	-	-	20.0	2.6
$MgSO_4$	-	-	-	-	-	5.0	0.6
H_2O	-	-	-	-	-	75.0	9.8
TOTAL	98.5%	99.6%	99.1%	99.5%	99.0%	100%	99.1%

TABLE 4

RECOMMENDED SAMPLES FOR THE PROPOSED DUST MELTING EXPERIMENTS-SHOWING LOCATIONS AND ESTIMATED TEMPERATURES TO MELT AND FLOW

1.	Volcanic Glass - 200 km downwind - - - - - - of Mt. St. Helens, Wasington State (MSH sample designation)	700° - 1000°C
2.	Gypsum - White Sands New Mexico- - - - - - - Windblown Playa Lake sediment (WSG sample designation)	900° - 1100°C
3.	Montmorillonite, Clay - commercial supplier - (MC - sample designation)	1000° - 1300°C
4.	Playa Lake Sediments - Yucca Valley- - - - - Nevada test site (NTS) (YVLS sample designation)	1100° - 1400°C
5.	Granitic soil - surface above gold - - - - - Meadows Granite, NTS (GMGS sample designation)	1200° - 1500°C
6.	Quartz - Monterey Beach Sand - - - - - - - - - commercial supplier (MBS sample designation)	1750° - 1850°C
7.	Carbonate - Dolomite, e-tunnel - - - - - - - portal area Rainier Mesa, NTS (RMD sample designation)	2250° - 2400°C
	→ Sublimate first to $CaO_t M_g O + CO_2 \uparrow$ at- - -	$\sim$ 900°C

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